UNIVERSITY OF ALBERTA

# A Surface to Subsurface Correlation of the Facies Present in the Transition Zone Between the Bearpaw Formation and the Horseshoe Canyon Formation near East Coulee, Alberta.

by

**Kimberly Laura-May Earle**

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

Department of Earth and Atmospheric Sciences

Edmonton, Alberta

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Aug. 25/03

## ABSTRACT

Deltaic and associated environments are interpreted to be present both in outcrops and in the subsurface in the transition zone between the Bearpaw Formation and Horseshoe Canyon Formation in Townships 27-29 and Ranges 18-20 west of the Fourth Meridian. Examination of nineteen outcrops, four drill cores and 100 geophysical well logs reveals the presence of at least two river-dominated delta lobes and two wave-dominated delta lobes. The stratal succession can be divided into four facies associations, and 5 depositional cycles which represent two complete parasequences and one partial parasequence.

This study reveals that the river-dominated East Coulee delta lobe, the lower-most delta lobe present in outcrops in the study area, was deposited in a conformable succession, which is contrary to some previous interpretations (ex. Rahmani, 1988 and Ainsworth, 1994). Also, the progradation of the commonly sharp-based delta front in the "EC" delta lobe was not the result of a forced regression.

Vertical and lateral facies associations in the wave-dominated delta lobes suggest that progradation was coincident with sea level rise.

## ACKNOWLEDGEMENTS

As I end my lifetime of learning at school and begin my lifetime of learning at everything else, it seems fitting to thank those people who have helped me in my academic career. Firstly, I would like to thank my supervisor, George Pemberton, who inspires his students and allows us a unique opportunity for independent thought. Secondly, I would like to thank Tom Saunders and Jason Lavigne, the resident Horseshoe Canyon gurus, for all of their help along the way. You both inspired me greatly, and I appreciate you putting up with my questions. More specifically, thank-you Tom, for sharing in my excitement on the fecal pellet paper, and thank-you Jay for editing part of my thesis. Also, thank you to the many other members of the IRG past and present who have become friends along the way. Especially, thank-you Rich (McCrea) for all of the paleo-help in the early fecal pellet days, and Rozie (Pak), for editing part of this thesis, and teaching me everything I ever wanted to know about kukersites...

Thirdly, I would like to thank my field assistant April Fenwick for putting up with the 40 degree heat, the backed-up sewer, the ticks, the snakes, the noseeums, my cooking and all of the other splendid things that are integral parts of field work. Thank-yous are also extended to all of the landowners who gave me access to their property for an entire summer, and to the other people of East Coulee who made my field season one to remember. These include: the people at the Atlas Coal Mine, the Digbys, the Dooleys, the Sands, the Rasmussens, Bob Audy, Barry Graham, Rod Roisine, and most especially Sharleen Douglas who was April's and my "Mother" throughout our stay. I can't tell you how much we appreciate everything you have done for us.

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# CHAPTER I

# INTRODUCTION AND BACKGROUND INFORMATION

## Introduction

The transitional zone between the Campanian Bearpaw Formation and Maastrichtian Horseshoe Canyon Formation that is exposed near East Coulee, Alberta, Canada, is a popular field trip and field course site. A day trip from either Calgary or Edmonton is easily accomplished (Fig. 1.1B), and many of the outcrops can be accessed directly from a major highway or road. In addition, a variety of clastic strata can be studied, ranging from fully marine through continental facies. As such, a number of researchers have conducted formal studies of the approximately 60 m thick sections that are exposed in the area (see Shepheard and Hills, 1970; Rahmani 1983, 1988; Saunders, 1989; Ainsworth, 1991, 1992 and 1994; and Lavigne, 1999). After more than 30 years of research, controversy still surrounds the interpretation of the depositional environments represented by the rocks. As is seen on Figure 1.1C, however, most of the previous work focused on the same series of outcrops (see Shepheard and Hills, 1970; Rahmani 1983, 1988; Ainsworth, 1991, 1992 and 1994; and Lavigne, 1999). This study focuses on a different set of outcrops, and also discusses the ichnological aspects which have not been studied in detail in most of the outcrops. Only Saunders (1989) and Lavigne (1999) discussed any detailed ichnology. In addition, the increased and improved well data results in a much clearer picture of the depositional environments represented by the rocks.

## Background Information

The upper Bearpaw Formation consists mostly of laminated marine shales and siltstones, with minor sandstone beds and clay lenses (Habib, 1981). The lower

Figure 1.1. Location of the study area.

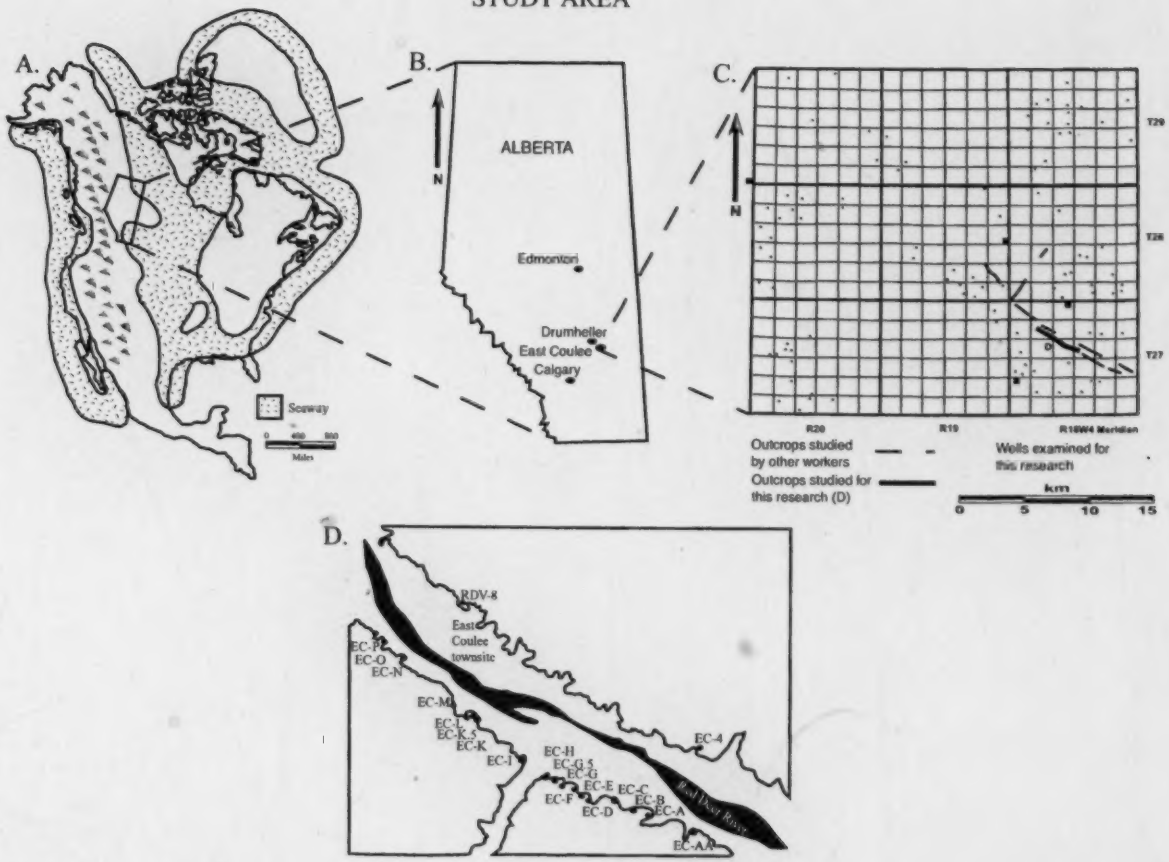
A. Early Maastrichtian Seaway during *Baculites baculus* time. Modified after Williams and Stelck (1975). Note that the study area is situated on the edge of a southeasterly oriented embayment.

B. Relative location of the study area within Alberta. The outcrops studied are located near East Coulee.

C. Location of the outcrops studied for this thesis, and the outcrops studied by previous workers. The outcrops studied for this thesis run parallel to some of the outcrops studied by previous workers.

D. Location of outcrops studied relative to the East Coulee townsite. RDV-8 is also discussed by Ainsworth (1991, 1992 and 1994) and Rahmani (1988) (EC-7). EC-4 is also discussed by Rahmani (1988).

## STUDY AREA


A.
Seaway
0 400 800
Miles
B.
N
ALBERTA
Edmonton
Drumheller
East Coulee
Calgary
C.
N
T29
T28
T27
R20
R19
R18W4 Meridian
Outcrops studied by other workers
Outcrops studied for this research (D)
Wells examined for this research
km
0 5 10 15
D.
RDV-8
East Coulee townsite
EC-P
EC-O
EC-N
EC-M
EC-L
EC-K.5
EC-K
EC-J
EC-H
EC-G.5
EC-G
EC-E
EC-C
EC-F
EC-D
EC-B
EC-A
EC-AA
EC-4
Red Deer River

Horseshoe Canyon Formation contains interbedded and interlensed fresh and brackish water sandstones, siltstones, and shales (Irish, 1970).

Coal seams are also common in the Horseshoe Canyon Formation. The Upper Cretaceous to Tertiary age coal seams present in the Red Deer River area were mined throughout most of the 20th century, and have thus received much attention. Some of the outcrops studied for this research are located directly behind the Atlas Coal Mine near East Coulee that operated until the late 1970's. The Atlas Mine has since been transformed into a museum that greets numerous tourists throughout the summer months.

Gibson (1977) identified fifteen prominent coal seams in the Red Deer River valley around East Coulee, Alberta (Fig. 1.1B). The coal nomenclature and numbering system used by Gibson (1977) was first proposed by Allan and Sanderson (1945). This same nomenclature and numbering system is used in this report. Ainsworth (1992, 1994) identified two additional coal seams in the study area, naming them Coal 1A and Coal 1B. These latter two coal seams, however, are not regionally extensive. Coal 0 (Gibson, 1977) is the most easily observable, and most regionally extensive coal seam in outcrop and in the subsurface in the study area.

Bentonite layers are also common in the Horseshoe Canyon Formation. These layers indicate that volcanic activity was contemporaneous to deposition. These bentonite layers can be used for dating, subdividing and correlating some stratigraphic units in the area.

The contact between the Horseshoe Canyon and Bearpaw formations is conformable (although diachronous) and youngs towards the east with marginal marine sediments of the Horseshoe Canyon Formation intertongueing with fully and marginal marine sediments of the Bearpaw Formation. The lower contact of the Horseshoe Canyon Formation is formally placed "arbitrarily at the base of the first thick, light

grey weathering sandstone above the chocolate-brown, sandy shales of the Bearpaw Formation" (Irish, 1970). The two formations often appear to be transitional with one another (Shepheard and Hills, 1970), and it is difficult to ascertain where one formation ends and the other begins. The precise location of the contact does not affect the interpretations presented in this study, though, as the two units are believed to be genetically related (Shepheard and Hills, 1970).

The exact age of the Horseshoe Canyon Formation is difficult to ascertain, due to the arbitrary placement and diachronous nature of the basal contact. The lack of an easily datable, regionally extensive marker near the base of the formation adds to this difficulty. Lerbekmo and Coulter (1985) stated that magnetostratigraphic dating in the study area indicates that the base of the Maastrichtian is at Coal 5, within the Horseshoe Canyon Formation (Gibson, 1977). This is coincident with the base of the *Baculites baculus* (ammonoid) biostratigraphic zone in the United States and the base of the *Scaphites (Hoploscaphites) constrictus-Inoceramus fibrosus* (ammonoid and pelecypod respectively) Zone in western Canada (Lerbekmo and Braman, 2002). According to Lerbekmo and Coulter (1985), this zone has an absolute date of 71 million years. These results are supported by the discovery of the genus *Wodehouseia* (palynomorph) just below Coal 5 by Srivastava (1970). Lerbekmo and Coulter (1985) indicated that the first appearance of this genus signifies the crossing of the Campanian-Maastrichtian boundary. As such, the transitional zone between the Bearpaw Formation and the Horseshoe Canyon Formation is late Campanian to early Maastrichtian in age.

The Horseshoe Canyon Formation was deposited during a time of significant tectonic activity in Western Canada. From the Middle Jurassic to the Paleocene, the Western Canadian foreland basin developed in response to deformation along the western edge of the North American craton (Dawson *et al*, 1994). Compressional tec-

tonics dominated, causing the upthrust of mountains and an accompanying flexure and loading of the underlying crust due to the increased weight of the mountains. Much of the sediment that comprises the Edmonton Group was shed due to the tectonic activity in the west and was deposited as an eastwardly prograding, eastwardly thinning wedge (Hamblin and Lee, 1997) in the West Alberta Basin (which had existed since the Devonian) (Fig. 1.2). The study area itself has relatively flat-lying rocks that have a shallow, northwesterly dip (Fig. 1.3), that reflects the overall structure of the basin. No obvious faulting is noted in the study area.

Throughout the Campanian and Maastrichtian, the Arctic and Gulf seas were connected by the Western Interior Seaway (Fig. 1.1A). This is indicated by faunal records containing both northern and southern fossil assemblages (Williams and Stelck, 1975). The study area is located in a southeasterly oriented embayment. The sediments present are believed to have been deposited as a prograding marginal marine to continental succession representing the final retreat of the Bearpaw Sea from the study area (Shepheard and Hills, 1970). Rahmani (1988) noted that this progradation was punctuated by several transgressions that resulted in the diachronous, interfingering contact described previously. As can be seen on Figure 1.4, at least some of the transgressions that punctuated the overall progradation of the Horseshoe Canyon Formation were caused by delta lobe switching. A multi-lobe deltaic complex is indicated to exist by the presence of repeating, coarsening upward cycles that exhibit lobeate geometries when mapped.

The sediments comprising the Horseshoe Canyon Formation were transported from the west by southeasterly flowing fluvial systems (Dawson *et al.*, 1994), and were reworked and redistributed by the Western Interior Seaway.

The Horseshoe Canyon Formation comprises the lowermost unit in the Edmonton Group. Conformably overlying the Horseshoe Canyon are the Whitemud and the

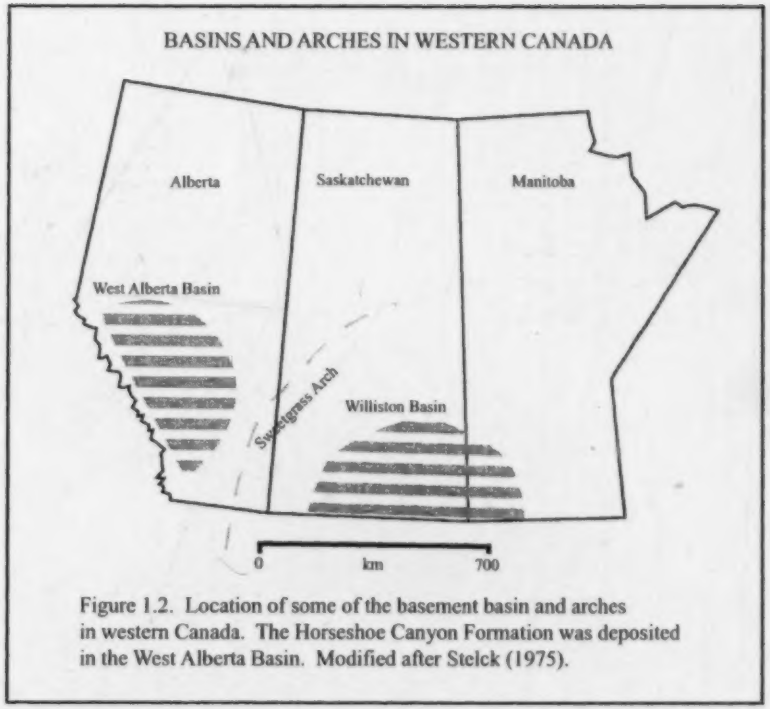



Figure 1.2. Location of some of the basement basin and arches in western Canada. The Horseshoe Canyon Formation was deposited in the West Alberta Basin. Modified after Stelck (1975).

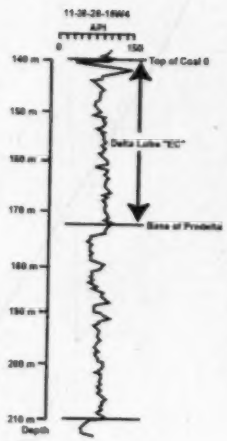
Figure 1.3. Structure contour maps of surfaces observed in geophysical well logs, drill cores, and outcrops.

A. Location of the base of the prodelta and the top of Coal 0 as seen in 11-28-28-18W4. This is a representative well log for the rocks in the study area.

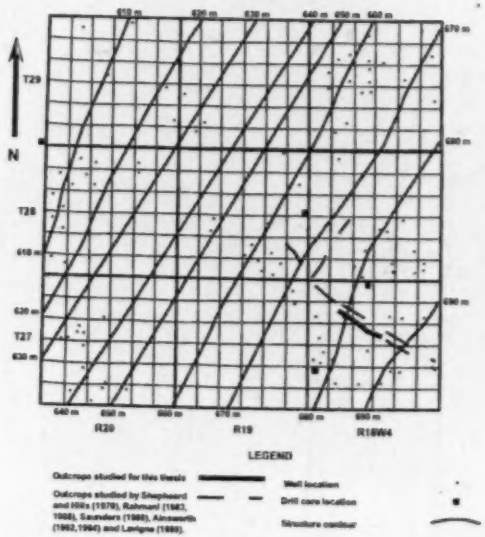
B. Structure contour map of the base of the prodelta in the EC delta lobe (see also fig. 1.4). This is the lowermost delta lobe that is observed in outcrops in the study area. Note that the surface is relatively flat, with a fairly constant dip towards the northwest.

C. Structure contour map of the top of Coal 0, which also marks the top of the EC delta lobe. This surface is also relatively flat, with a constant dip towards the northwest.

A.




B. STRUCTURE CONTOUR MAP OF THE BASE OF THE PRODELTA




C. STRUCTURE CONTOUR MAP OF THE TOP OF COAL 0

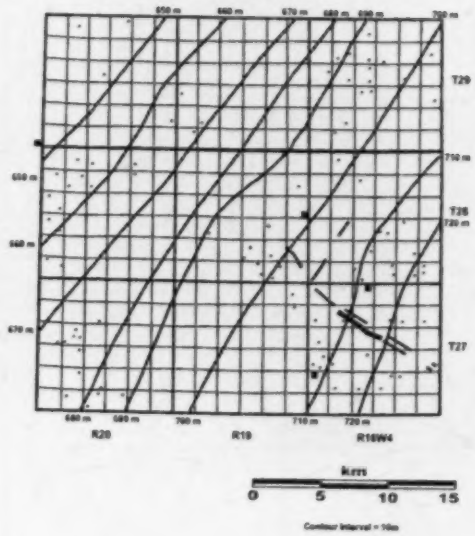
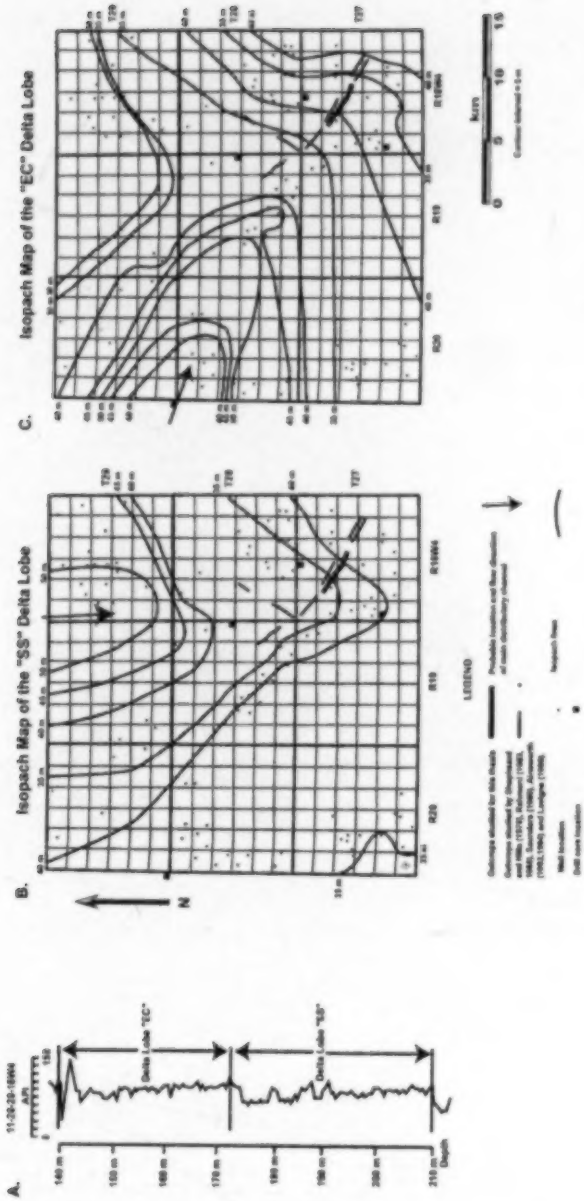


Figure 1.4. Isopach maps of two delta lobes present in the Bearpaw Formation to lower Horseshoe Canyon Formation transition zone.

A. Gamma ray log 11-28-28-18W4 showing the two coarsening upward cycles that are interpreted to represent the two delta lobes.

B. Isopach map of the "SS" delta lobe. Delta lobe "SS" refers to the lobe that is recognized in the subsurface in the study area, but not in the outcrops. This delta lobe directly underlies the "EC" delta lobe. Note the interpreted position of the main distributary channel in the north.

C. Isopach map of the "EC" delta lobe that is recognized in both the subsurface, and in the outcrops near East Coulee, Alberta. The "EC" delta lobe directly overlies the "SS" delta lobe, and is capped by Coal 0. Note the interpreted position of the main distributary channel in the northwest.


C.
Isopach Map of the "EC" Delta Lobe
km
0
5
10
15
B.
Isopach Map of the "SS" Delta Lobe
N
LEGEND
A.
Delta Lobe "EC"
Delta Lobe "SS"
Depth

Battle formations, and conformably underlying the Horseshoe Canyon is the Bearpaw Formation (Fig. 1.5). The Whitemud and Battle Formations together with the Horseshoe Canyon Formation comprise the Edmonton Group. The Knee Hills Tuff Zone which is a useful stratigraphic marker for Upper Cretaceous sediments lies within the Battle Formation.

To the northwest beyond the depositional edge of the Bearpaw Formation, sediment that is age equivalent to the Horseshoe Canyon Formation forms part of the upper Wapiti Formation.

Near the deformed belt in the northern and central foothills, Campanian and Maastrichtian age rocks are referred to as the Brazeau Formation.

In southern Alberta, an age equivalent to the lower (marine) Horseshoe Canyon Formation is referred to as the Blood Reserve Member and an age equivalent to the upper (non-marine) Horseshoe Canyon Formation is referred to as the St. Mary's River Formation. The Eastend Formation in southwestern Saskatchewan is also an age equivalent to the upper Horseshoe Canyon Formation.

In the United States, age equivalents include Idaho's Lance Formation, and Wyoming's Fox Hills Formation. The Fox Hills Formation is lithologically similar to the Horseshoe Canyon Formation, and contains many of the same types of body and trace fossils (see Waage, 1968 and Land, 1972).

Most of the economic interest in the Horseshoe Canyon Formation has focused on its many coal seams that were mined during much of the 20$^{th}$ century. However, recent discoveries of hydrocarbons in the Horseshoe Canyon Formation, and other shallow clastic formations have sparked a renewed interest in the formations' economic potentials. In fact, a number of Horseshoe Canyon Formation gas wells exist to the west of the study area (see Earle, 2001). One of the producing sand bodies was interpreted to represent a wave-dominated shoreface complex (Earle, 2001). This

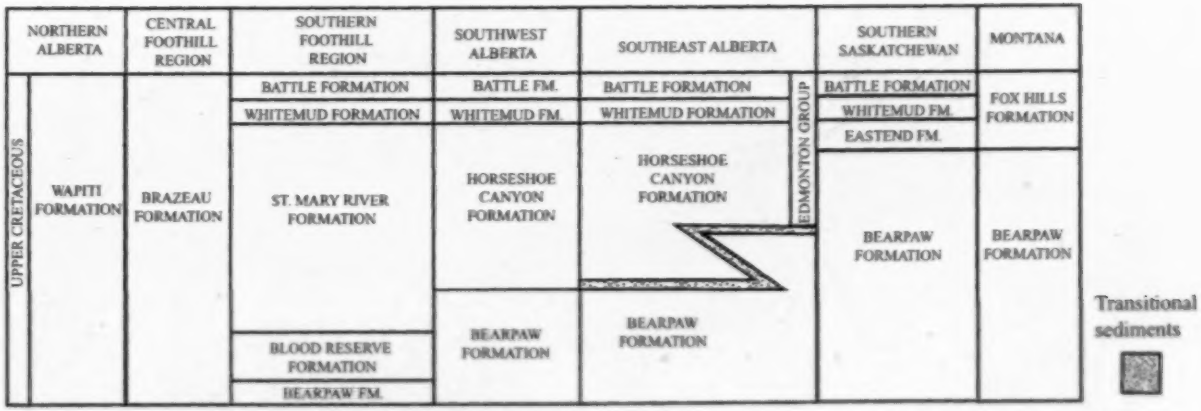



Figure 1.5. Upper Cretaceous stratigraphy. Modified after Irish (1970) and Dawson *et al.* (1994). Note that the Bearpaw Formation and the Horseshoe Canyon Formation are transitional in the study area.

wave-dominated shoreface complex appears to directly underlay the "SS" Delta Lobe mapped in Fig. 1.4B. It is possible that the producing sand body is genetically related to the delta complex discussed in this thesis, although further study is required to verify this.

**Study Area (Fig. 1.1)**

The study area is located in Townships 27-29, Ranges 18-20, West of the 4th Meridian (Fig. 1.1B). The outcrops studied for this project are located on the south side of the Red Deer River near the townsite of East Coulee, Alberta, Canada, in Township 27, Range 18, West of the 4th Meridian (Fig. 1.1C). Approximately 4 kilometers of continuous outcrops oriented northwest-southeast were studied for this thesis. These outcrops are believed to approximate a depositional dip cross-section. The outcrop intervals studied average 65 meters thick and comprise marginal marine to fully marine sediments with abundant and diverse physical and biogenic sedimentary structures.

**Previous Work**

The first significant study of the Upper Cretaceous to Tertiary sediments in the Red Deer River area was completed by Tyrrell (1887). This, along with other early works including Allan (1918, 1922), Sanderson (1931), Allan and Rutherford (1934), and Allan and Sanderson (1945) provided the groundwork for all future sedimentological and stratigraphical studies of the lower Cretaceous in the study area.

Ower (1960) completed the first regional stratigraphical study that focused on the Edmonton "Formation" in both outcrops and subsurface data. More in-depth subsurface correlations of the Edmonton "Formation" were completed by Elliot (1960). Irish (1970) completed focused sedimentologic and stratigraphic studies of

the Edmonton "Formation", and elevated its status to the Edmonton Group. Irish (1970) also elevated the Whitemud and Battle units to formational status, and proposed the name Horseshoe Canyon Formation for the strata between the Bearpaw and Whitemud Formations. Later studies by Williams and Stelck (1975), and Stelck (1975) helped to place the Horseshoe Canyon and Bearpaw Formations into a paleogeographic and tectonic framework. Many of the relationships described above were briefly summarized by Dawson *et al.* (1994).

The different interpretations of the outcrops present around East Coulee reflect the advances in, and changes in facies models over time. The first detailed sedimentologic and stratigraphic study of the transitional zone between the Horseshoe Canyon Formation and the Bearpaw Formation in outcrops in the study area was completed by Shepheard and Hills (1970). Six sedimentary units named BP, E1, E2, E3, E4, and E5 were recognized based on lithologies, lithologic sequences, bedding types and sedimentary structures. Shepheard and Hills' (1970) units BP and E1 directly correspond to Facies 1 to 7 (Fig. 1.6) with Coal 0 (Facies 7) marking the top of unit E1. Shepheard and Hills (1970) interpreted these units to represent a conformable succession of deltaic and associated facies. Most of these analogies were drawn from the modern Mississippi delta. Waheed (1983) studied many of the same sediments in an area located approximately 8 km northwest of Shepheard and Hills' (1970) study area, and also interpreted them to represent deltaic and associated environments.

Rahmani (1988) re-evaluated the outcrops studied by Shepheard and Hills, but disagreed with some of their interpretations. Rahmani (1988) also interpreted some of the sediments exposed below Coal 0 to represent wave-dominated prodelta and delta front deposits that represent progradation of the shoreline in a deltaic setting. Rahmani (1988) stated, however, that an unconformity exists at the top of the proximal delta front (top of Facies 4 on Fig. 1.6) and that after the deposition of

Figure 1.6. Example litholog of the rocks observed at EC-B. See fig. 1.1D for location of outcrop. Height refers to height above base of outcrop. The "Facies" column shows the number assigned to each facies in this thesis. The "Depositional Cycle" column refers to the interpreted depositional units discussed in Chapter 3.

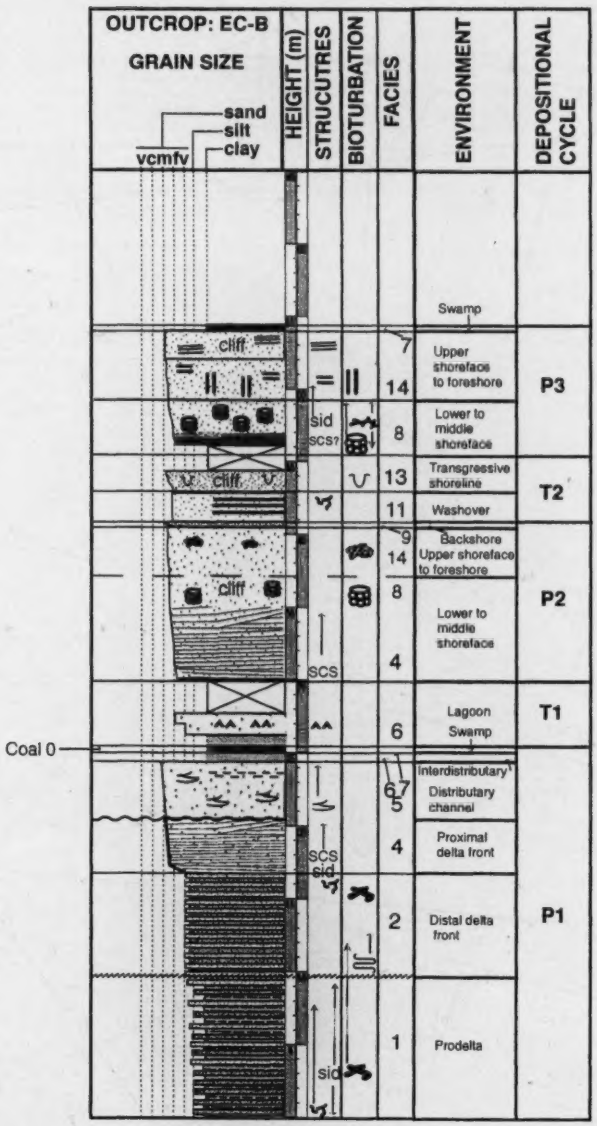
The P1-Progradational Cycle appears to correspond with Shepheard and Hills' (1970) Units BP and E1, Rahmani's (1988) Unit 1, Saunders' (1989) R1 regressive cycle, and Ainsworth's (1992 and 1994) allomembers A and B.

The T1-Transgressive Cycle appears to correlate to the lower portion of Shepheard and Hills' (1970) Unit E2, the lower portion of Rahmani's (1988) Unit 2, Saunders' (1989) transgressive cycle T2, and the lower portion of Ainsworth's (1992 and 1994) allomember C.

The P2-Progradational Cycle is believed to correspond with Shepheard and Hills' (1970) Unit E2, the upper portion of Rahmani's (1988) Unit 2, Saunders' (1989) R2 regressive cycle and the upper portion of Ainsworth's (1992 and 1994) allomember C.

The T2-Transgressive Cycle appears to correspond with Shepheard and Hills' (1970) Unit E3, Rahmani's (1989) Unit 3, Saunders' (1989) T3 transgressive cycle, and Ainsworth's (1992 and 1994) allomember D and possibly allomember E.

The P3-Progradational Cycle appears to correlate to Shepheard and Hills' (1970) Unit E4 and part of E5, Rahmani's (1988) Unit 4, Saunders' (1989) R3 Appaloosa cycle, Ainsworth's (1992 and 1994) allomember F and possibly allomember E.




Legend

Physical Sedimentary Structures

Trough Cross-bedding
Wavy Bedding
Lenticular Bedding
Swaley Cross-stratification SCS
Ripples
Low angle, parallel bedding
Planar, horizontal bedding
Tabular Cross-bedding
Synaeresis Cracks

Biogenic Sedimentary Structures

*Helminthopsis*
*Gyrochorte*
*Bergaueria*
*Macharoichnus*
*Arenicolites*
*Skolithos*
*Paleophycus*
*Planolites*
*Chondrites*
*Thalassinoides*
*Teichichnus*
*Ophiomorpha*
*Teredolites*
Unknown burrow

Accessories

Carbonaceous Debris
Siderite sid
Shale laminae
Coaly laminae

Contacts

Sharp
Inferred sharp
Gradational
Erosional/Unconformable

Other

Present throughout interval
Present in some places in interval
Very prominent/cliff-forming unit cliff

HEIGHT= Height above outcrop base

the deltaic sediments, the area experienced emergence of portions of the delta, base level fall, and deepening and seaward extension of the distributary channels. A rooted horizon present at the top of the delta front at RDV-8 (Fig. 1.1d) is noted to be evidence for subaerial exposure and vegetation. Rahmani (1988) indicated that a subsequent relative sea level rise then occurred and the distributary channels experienced tidal estuarine conditions for a minimum of 35 km on the seaward side. A tripartite estuarine model was invoked to explain the facies relationships in the area. Figure 1.7 shows the position of the estuary mapped by Rahmani (1988). These analogies were drawn in part from the Georgian Atlantic coast in the United States, the Rhine Delta of the southwest Netherlands and the estuaries of western France, such as the Gironde Estuary.

Eberth (1996) discussed the nature of a number of channels present in the Horseshoe Canyon Formation and concluded that Facies 4 (fig. 1.6) represents an estuarine channel.

Ainsworth (1991, 1992 and 1994) reinterpreted the outcrops studied by Shepheard and Hills (1970) and Rahmani (1988) using a combination of allostratigraphic and sequence stratigraphic techniques. This reflects the growing popularity of these new types of stratigraphy. Ainsworth (1991, 1992 and 1994) subdivided the succession into seven informal allomembers that are bounded by flooding surfaces. Each allomember contains both a transgressive and a regressive phase. In addition, each allomember was interpreted to have a fourth order periodicity of 140, 000 years. Overall, Ainsworth (1991, 1992 and 1994) interpreted the sediments to represent three fourth order sequences that constitute part of one third order sequence.

Ainsworth (1991, 1992 and 1994) concurred with most of Rahmani's (1988) interpretations of the facies succession below Coal 0 (Fig. 1.5). Ainsworth (1992, 1994) agreed that Facies 5 (Fig. 1.6) represents estuarine deposits, and places a

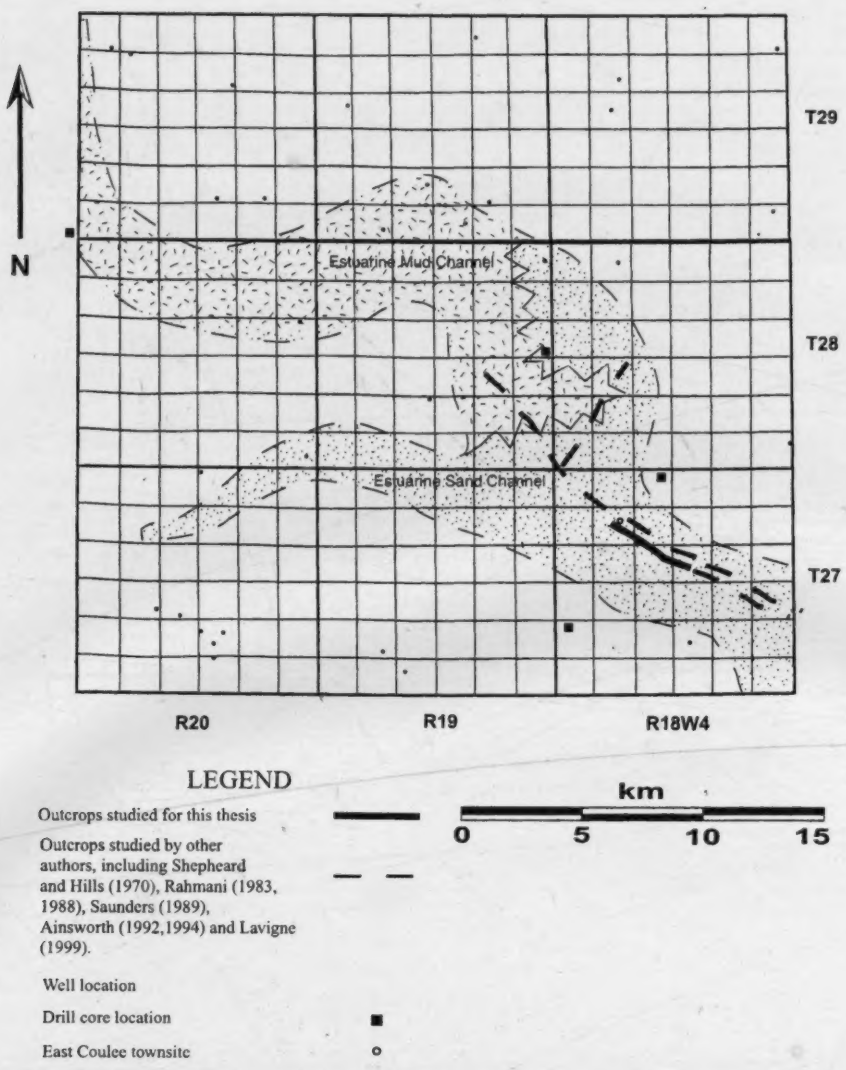



Figure 1.7. Location of Rahmani's (1988) estuary. Note that there were fewer wells that penetrated the EC delta lobe at the time this was published than there are today (see Fig. 1.1C for comparison.

sequence boundary at its base. Ainsworth (1991, 1992 and 1994) referred to Facies 1-3 (fig. 1.6) as a shoreface succession, though, rather than a deltaic succession. These two environments, however, often have similar facies.

Ainsworth (1991, 1992 and 1994) also suggested that at least one of the sharp-based shorefaces in the succession is indicative of forced regressions. That is to say, a relative sea-level fall progressively exposed the sea floor, causing the shoreline to migrate seaward (Posamentier et al., 1992). Overall, Ainsworth (1991, 1992 and 1994) emphasized the dominance of allocyclic controls on deposition of the sediments.

Lavigne (1999) studied outcrops north and northwest of the outcrops examined for this thesis. Many of these outcrops were also discussed by Shepheard and Hills (1970), Rahmani (1988) and Ainsworth (1991, 1992 and 1994). The present research discusses the ichnological, sedimentological and stratigraphical aspects of the rocks, with a focus on the *Teredolites* ichnofacies.

Lavigne (1999) agreed with many of Shepheard and Hills' (1970) interpretations, and disagreed with many of Rahmani's (1988) and Ainsworth's (1991, 1992 and 1994) interpretations. Lavigne (1999) argued that the stratal succession being discussed represents a single genetically related succession of deltaic facies. That is, Facies 5 (Fig. 1.6) represents distributary channels that are genetically related to the underlying facies. Lavigne (1999) indicated that there was no conclusive evidence for the presence of a sequence boundary at the top of Facies 4 (Fig. 1.6) (and hence, these channels do not represent incised valleys).

Saunders (1989) studied outcrops southeast (paleo-seaward) of the outcrops studied for this thesis and those studied by other researchers. This research consists of a complete review of the ichnologic and sedimentologic aspects of the informally named Appaloosa sandstone. This unit correlates to Shepheard and Hills' (1970)

Unit E5, Rahmani's (1983) Unit 4, Ainsworth's (1991, 1992 and 1994) allomember F, and the P3-progradational cycle at EC-B (Fig. 1.6). As such, Saunders (1989) does not discuss the previously mentioned controversies regarding the units below Coal 0. Saunders (1989) research is quite significant to interpretations of the facies in the area however, as it focuses on the significance of the trace fossils present. This information greatly aids with interpretations of the units overlying Coal 0, as many of the facies present in Saunders' (1989) outcrops are present in the study area.

**Purpose**

The primary objective of this study is to construct a detailed depositional model of the transitional zone between the Bearpaw Formation and lower Horseshoe Canyon Formation. The model is based on ichnologic, sedimentologic, and stratigraphic data collected from outcrops. Studying a series of outcrops that have not been previously considered may provide the necessary data to solve the controversies regarding the interpretations of facies in this area. In most of the previous studies, relatively little attention was paid to the ichnological aspects of the rocks. Hence, a complete ichnological review may assist greatly with delineating the facies variability. In addition, the amount of, and quality of subsurface data available has greatly increased in recent years. Increased numbers of improved geophysical well logs as well as drill cores greatly assist with understanding the facies distributions.

This detailed depositional model will aid in future paleodepositional reconstructions of the Bearpaw Formation and lower Horseshoe Canyon Formation transitional zone and other similar systems, and may increase understanding of the depositional processes acting during the Upper Cretaceous.

**Thesis Outline**

Chapter II of this thesis provides detailed facies observations and discusses the interpretations of the facies and facies associations. The focus of Chapter III is on the interpreted stratigraphic relationships and facies distributions observed in the rocks. This chapter explains the depositional history of the rocks, and discusses the similarities and differences noted between this, and other previous studies in the area. Chapter V presents conclusions.

# CHAPTER II

# FACIES OBSERVATIONS AND INTERPRETATIONS

## Facies Observations and Interpretations

Walker (1992) defined the term facies as "a body of rock characterized by a particular combination of lithology, physical and biological structures that bestow an aspect ("facies") different from the bodies of rock above, below and laterally adjacent." Describing bodies of rock in non-genetic terms is important, so that other workers clearly understand what was observed, but can still arrive at their own conclusions. The facies are described in more detail here than in many previous studies so that readers gain a comprehensive understanding of the rock units and can fully evaluate the stratigraphic and paleogeographic discussion in Chapter III.

The facies descriptions are based primarily upon data obtained from approximately 4 km of nearly continuous outcrops. These facies descriptions are further enhanced by data obtained from four drill cores. This together with approximately 100 geophysical well logs assisted in mapping and understanding the distribution of facies, which is discussed in Chapter III. Fortunately, recent interest in shallow gas plays has lead to a significant increase in both drilling, and shallow well logging in the area. Much more subsurface data exists now than when previous studies were published, and the increased data greatly aids with interpretations.

Fourteen facies, and four facies associations are recognized. Most of the facies are widespread throughout the study area. Some facies are present in more than one facies association, as bodies of rock with similar characteristics can be present in different environments.

Facies 1: Interlaminated and Interbedded Mudstone and Siltstone with Moderately Abundant *Helminthopsis* (fig. 2.1)

*Description*

Facies 1 (F1) is the basal facies exposed in outcrops in the Bearpaw-Horseshoe Canyon Formation transition zone in the study area (Fig. 2.1A). F1 is only exposed in the most southeasterly and most northwesterly outcrops, but not in the central outcrops. The exposed apparent thickness ranges from 1-9.2 m, with an average of 9 m. F1 is approximately 10 m thick in drill cores. The lower contact of F1 is not exposed. Where observed, F1 always underlies Facies 2 (F2). The contact between the two facies is always gradational in the southeast, but is either gradational or sharp in the northwest. The contact is horizontal and flat, with no evidence of significant erosion along the horizon.

Weathering commonly causes a characteristic "popcorn" texture to develop on the surface of the sediment that obscures the true nature of the rock (Fig. 2.1B). When broken apart for further examination, the unit commonly emits an earthy odour. Always appearing layered or striped, F1 exhibits grey, brown and orange coloration. The orange coloration is attributed to siderite that is present throughout much of the unit. Sediment commonly becomes lighter in color up section. Although most of the unit is recessive in nature, prominent, cobble-like siderite beds are common. These siderite beds tend to be thin, rarely reaching more than 5 cm in thickness. The siderite content often increases up section.

F1 consists primarily of a coarsening upward succession of interlaminated and interbedded mudstone and siltstone, with some rare beds of lower very fine grained sandstone. Very fine grained sand beds are typically only seen in the upper portion of the unit, as F1 grades into F2. The basal, more muddy beds are commonly quite friable, and may be completely unconsolidated. Where particularly friable or

Figure 2.1. Prodelta deposits (F1) in outcrop. F1 belongs to Facies Association 1 (FA1).

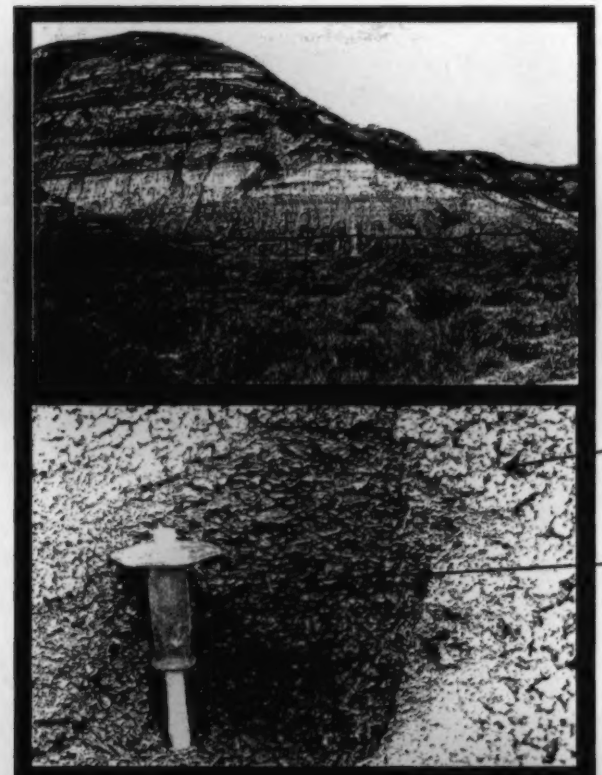
A. F1 in outcrop, at EC-C. F1, where present, always underlies F2. Note that F1 is darker in color than F2, due to an increased amount of mud in F1.

B. Close-up view of F1 in outcrop at EC-A. Note the weathered, "popcorn" texture seen on the surface. Also note the muddy, crumbly nature of the rock that can obscure physical and biogenic sedimentary structures.

C. Abundant *Helminthopsis (He)* in F1 at EC-D. This is the most common trace fossil seen in F1.

A.

B.




C.

unconsolidated, sedimentary and biogenic structures are difficult to see.

Most beds and laminae are horizontal and flat, and display sharp contacts with underlying and overlying beds. The apparent bed thickness tends to be a few centimeters or less, with the apparent thicknesses remaining constant or increasing up section. Sediments in the far northwest are an exception to this, as the bed thickness decreases up section. The uppermost few meters of the facies sometimes appear to be rhythmically bedded.

Variable concentrations of carbonaceous debris are common throughout most of F1. Most of the carbonaceous debris is equal to or less than 1-2 mm in diameter, and is mostly present along bed or lamination contacts.

Trace fossils are dominantly tiny, unbranched, dark, mud-filled structures identified as *Helminthopsis* (Fig. 2.1C). The commonly abundant *Helminthopsis* are diminutive, with diameters between 1-2 mm. Typically, the trace fossils are isolated to discrete beds and intervals that are not laterally extensive. Bioturbated beds can rarely be traced for more than a few meters horizontally. The burrow traces are present throughout the entire vertical range of the unit and are present in all lithologies of F1. Locally increased amounts of carbonaceous debris are commonly associated with the *Helminthopsis*.

Where the upper contact is sideritized, it may contain *Gyrochorte* on the bedding surface. The traces are unbranched, with 0.5 cm wide, straight to slightly curving trails. The longest observed trail length is approximately 5 cm, but the trails could be longer as the samples are quite weathered. Although *Planolites* are not observed in the outcrops, they are moderately abundant in drill cores.

*Interpretation*

Facies 1 is interpreted to represent deposits that were formed in a prodelta environment (see fig. 2.2). Prodelta deposits are composed of the finest grained

Schematic Diagram of a Delta

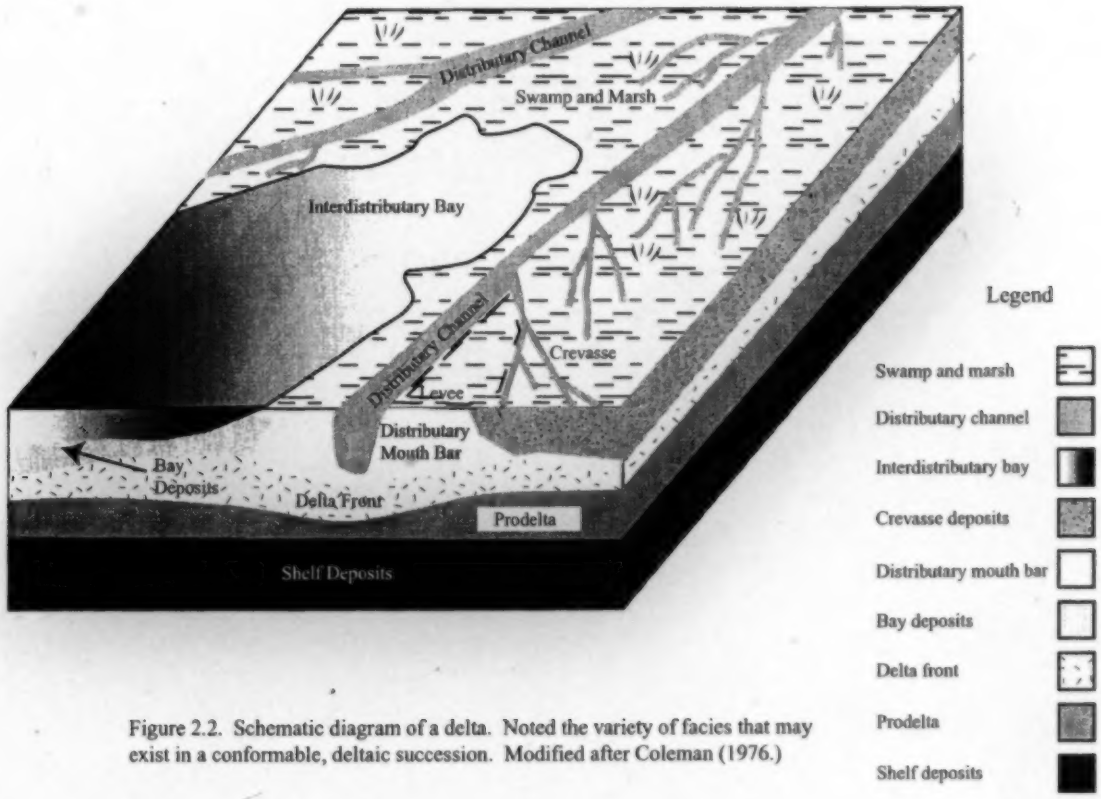



Figure 2.2. Schematic diagram of a delta. Noted the variety of facies that may exist in a conformable, deltaic succession. Modified after Coleman (1976.)

sediment in the delta (Coleman and Prior, 1982), such as the silts and clays observed in F1. These silts and clays likely settled out of suspension, under calm, low energy, generally fairweather conditions. This is reflected by the horizontal, predominantly flat-lying beds. The presence of very rare, very fine grained sandstone beds in the lower and middle portions of the facies may be the result of storm currents (Reading and Collinson, 1996), increased discharge during floods, or changes in relative water densities. However, the presence of these same beds in the upper portion of the facies is likely due to the upward and landward grading into coarser sediments deposited nearer the river mouths (Coleman and Prior, 1982).

Rhythmic bedding is also common in the prodelta. Moslow and Pemberton (1988) indicated that a rhythmic pattern to the distribution and deposition of beds may reflect cyclical sedimentary events such as seasonal flooding.

The abundance of tiny carbonaceous debris throughout the facies likely reflects close proximity to a river mouth, as suggested by Rahmani (1988). The organic debris is derived from a more continental location, and broken up and transported downstream to the offshore and shoreface. High amounts of preserved organic matter is common in deltas with some river dominance (Bhattacharya and Walker, 1992). The debris may also have been deposited as seasonal pulses of phytodetritus similar to that described by Rice *et al.* (1986).

The siderite in the unit is considered to be diagenetic. A discussion of the geochemical conditions required for sideritization is found in Berner (1981).

The trace fossil assemblage is characteristic of an environmentally stressed *Cruziana* ichnofacies, similar to that described in the Dunvegan Formation by Gingras *et al.* (1998). Pemberton *et al.* (1992) indicated that a normal *Cruziana* ichnofacies is typified by a mixed association of vertical, inclined, and horizontal structures, created by mobile organisms, high abundance and diversity and feeding and grazing

structures constructed by deposit feeders. In addition, the *Cruziana* ichnofacies is common in subtidal, poorly-sorted, and unconsolidated substrates and in low to moderate energy environments (Pemberton *et al.*, 1992). The trace fossil assemblage in F1 fits some of these criteria, but not all of the criteria. This is because the trace fossil assemblage reflects deposition in a river-dominated environment, which is a stressful habitat for organisms. Some common stresses that are deterrents to infaunal burrowing include fluctuating temperature and oxygen levels (Gingras *et al.*, 1998) and variable salinity levels. Coleman and Prior (1981), Moslow and Pemberton (1988) and Gingras *et al.* (1998) suggested that the fluctuating sedimentation rates are also possible deterrents to burrowing. Gingras *et al.* (1998) indicated that a reduced diversity and size of ichnofossils, and a suppression of feeding and grazing structures are suggestive of a river-dominated prodelta.

*Helminthopsis* is common in both the transitional offshore and wave-dominated prodelta environments (Saunders, 1989; Gingras et al., 1998 and MacEachern, 2000). It is likely that *Helminthopsis* is the dominant trace in the prodelta in the Horseshoe Canyon-Bearpaw Formation transition zone because its tracemaker(s) were abundant and well-adapted, and its grazing strategy was the most effective under the conditions.

Facies 2: Interlaminated and Interbedded Siltstone and Sandstone with Moderately Diverse Trace Fossil Assemblage (Fig. 2.3 & 2.4)

*Description*

Ranging in apparent thickness from 3 to 9.4 m, the average apparent thickness of Facies 2 (F2) is 6.7 m. F2 either gradationally or sharply overlies F1. F2 is the basal unit in measured sections where F1 is not present. F2 is overlain by Facies 4 (F4) in most outcrops (Fig. 2.3A) except in the far northwest, where it may be over-

Figure 2.3. Distal delta front (F2 and F3) deposits in outcrop and core. F2 and F3 belong to FA1.

A. F2 from a distance at EC-A. Note that F2 is darker in color than F4 reflecting a greater mud content.

B. A siderite bed manifested as rhombohedral bricks at EC-D. Scale bar is 15 cm long. The siderite beds are manifested in a number of ways including the bricks, cobbles, and grid-like cracks.

C. *Chondrites* (*Ch*) in a siderite bed at EC-B. Scale bar is 15 cm long. The *Chondrites* are more visible in the siderite than in the mudstone, siltstone and sandstone, likely because the siderite is more cohesive.

D. Large *Teichichnus (Te)* in F3 in core at approximately 155 m depth at 1-24-28-19W4. Scale bar is in 15 cm long. Note that the burrow trace is much more robust than the burrow traces present in the F2.

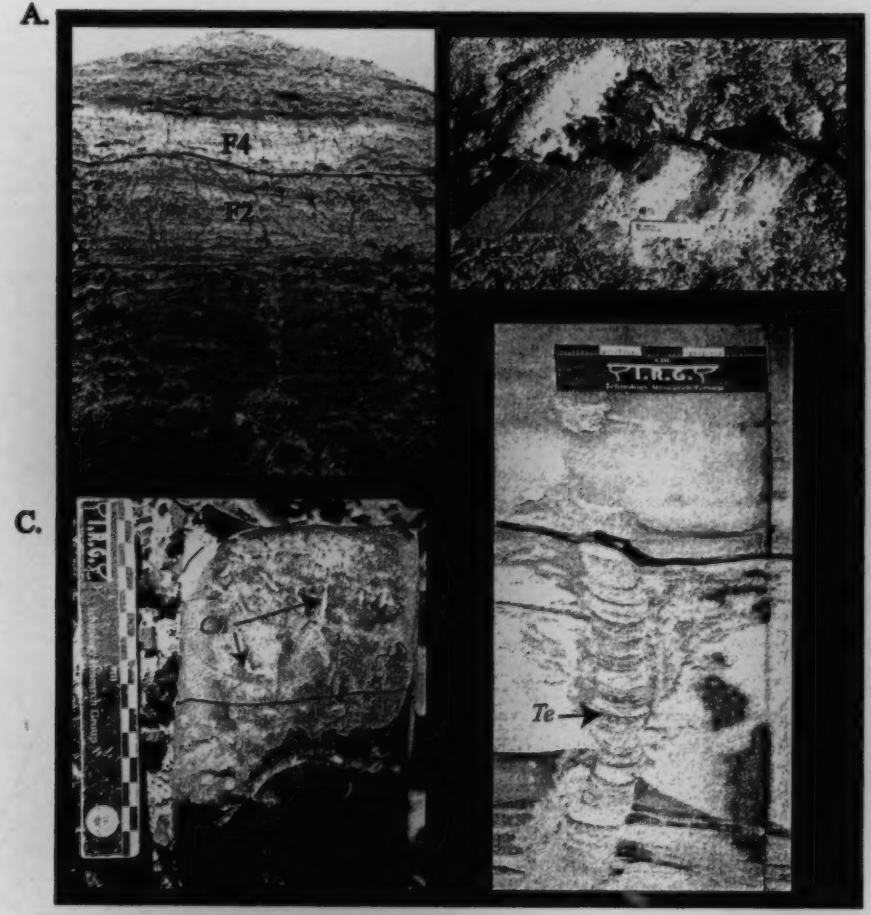

A.
B.
C.
D.
F4
F2
Te

Figure 2.4. Facies 2 in outcrop.

A. Tiny *Helminthopsis (He)* at EC-C. *Helminthopsis* is the most abundant ichnofossil in F2.

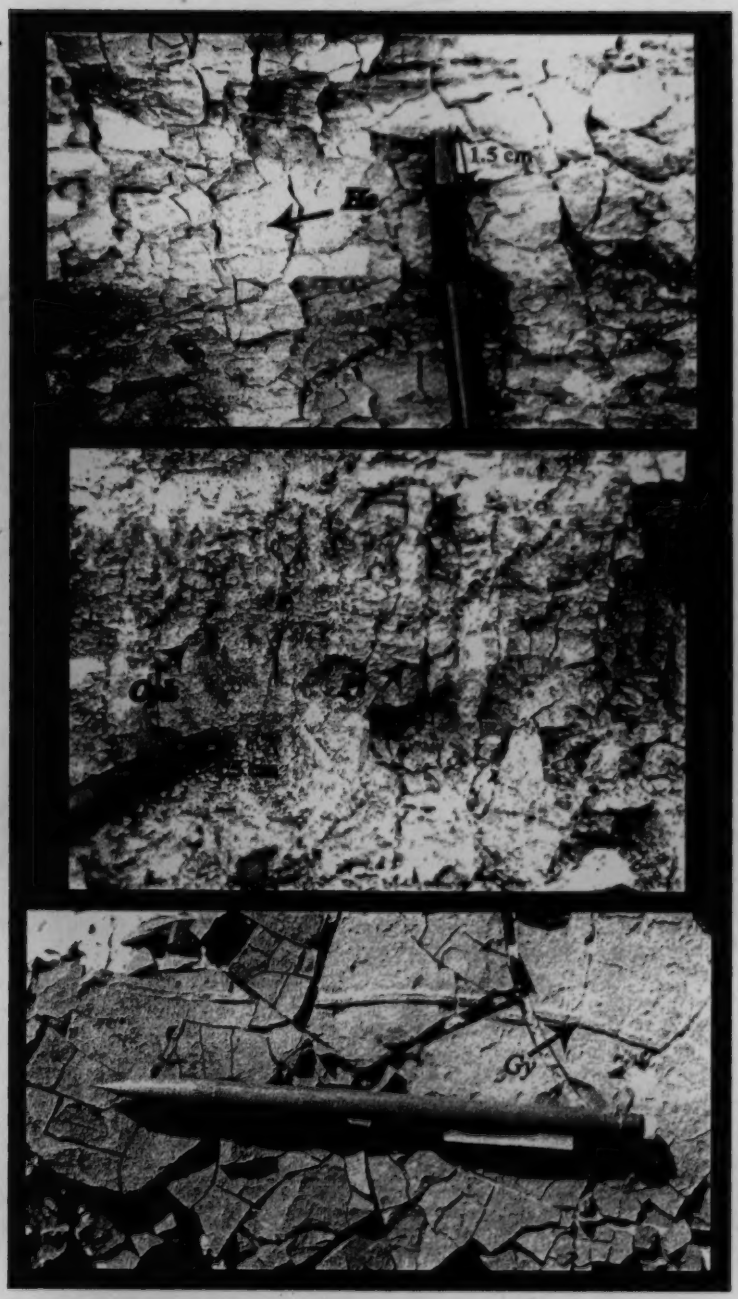
B. EC-A. *Planolites (Pl)* and *Ophiomorpha (Oph)*. Note that the *Ophiomorpha* is quite small, compared to the *Ophiomorpha* seen in other facies. *Planolites* and *Ophiomorpha* are commonly observed together.

C. *Gyrochorte (Gy)* in a siderite bed at EC-D. Pencil is 15 cm long. *Gyrochorte* is only present in siderite beds, and not in siltstone or sandstone beds. This is likely because the siderite is more cohesive, and as such, the burrow traces are easier to see.

A.

B.

C.



lain by Facies 8 (F8). Whether overlain by F4 or F8, the upper contact is sharp in all measured sections except EC-A and EC-H where it is gradational. This contact is both flat-lying and conformable throughout, and is commonly marked by a prominent siderite horizon. The siderite along this horizon manifests itself in a number of ways, including as cobbles, rhombohedral bricks (Fig. 2.3B) and a polygonal grid that resembles mud cracks. In addition, the siderite horizons may contain sideritized clasts that are 1-2 cm across or less. Overall, F2 is more sideritized than F1, and has more prominent siderite layers than does F1.

F2 exhibits a striped profile similar to that of F1, but is lighter in color throughout. This is due to the higher abundance of sand in F2 than in F1. The unit also becomes lighter in color up section. Typical colors range from orange-beige to tan, light brown and light grey. The orange stripes and orange tinting of beds is attributed to the siderite present in the sediment. F2 also displays the "popcorn" surface texture as seen in F1, but is harder and more cohesive than F1.

F2 contains interbedded and interlaminated silt and fine grained sandstone with rare mud beds and/or laminae, and coarsens upward overall. Especially in the upper portions of the unit, most of the mud sized particles are manifested as thin, planar parallel laminae within thicker sand beds. Normally graded beds are common. In some instances, the upper portion of the unit contains rhythmically bedded sand and shale, or repeating 0.5 cm thick fining upward cycles. Bed thickness tends to be greater than in F1, typically up to about 5 cm thick. In addition, the bedding thickness tends to increase upwards in the section (especially the sand bed thickness). The number of silty laminae also increases up-section in a number of cases. Most of the beds are sharply based, horizontal and flat. Lenticular bedding is also common. F2 is more cohesive than F1.

Carbonaceous debris averaging between 1-2 mm with a maximum of 2 cm in

diameter is moderately abundant in F2, but decreases in abundance up section. Most of the carbonaceous debris lies along horizontal bedding planes, but some of the debris drapes tiny ripples.

Bioturbation in F2 is more abundant and more diverse than in F1. *Helminthopsis* (Fig. 2.4A) are most common, appearing as muddy burrows in the silty fraction. *Chondrites* (Fig. 2.3C) and *Arenicolites* are also relatively common, especially in the siderite layers. The diameter of the *Chondrites* is never more than a few mm. The presence of *Arenicolites* is inferred from the appearance of paired burrow apertures, although the U-shaped portion of the burrow is not observed, however. The burrow trace diameter tends to be 0.5 cm or less.

*Ophiomorpha* is observed more rarely, in burrowed beds which are up to 10 cm thick (Fig. 2.4B). The burrows are predominantly vertical, and are approximately 1 cm in diameter. The beds containing the burrow traces are commonly associated with the planar parallel mud laminae and lenticular bedding. *Ophiomorpha* observed in F2 tends to be smaller and less widespread than most of the *Ophiomorpha* observed in the other facies. The *Ophiomorpha* in F2 also tend to have a greater vertical component than *Ophiomorpha* in other facies.

Also observed are sideritized *Planolites* that are about 2 millimeters to 1 centimeter in diameter (Fig. 2.4B). The *Planolites* are mostly sub-horizontal to horizontal and either occur monospecifically in thin (3 cm to 4 cm thick) beds slightly below the F2-F4 contact, or associated with the *Ophiomorpha* beds.

*Gyrochorte* is observed at the F1-F2 contact. *Gyrochorte* is also seen periodically at the sideritized F2-F4 contact (Fig. 2.4C). The ichnofossils are approximately 0.4 cm across and slightly curved. The maximum observed burrow length is approximately 15 cm. *Lockeia* is present locally.

*Interpretation*

Facies 2 is interpreted to represent a river-dominated distal bar (Coleman and Prior, 1981) or river-dominated distal delta front (Reading and Collinson, 1996) environment (Fig. 2.2). The distal bar environment is characterized by slightly coarser sediments (silts and very fine grained sandstones) than the prodelta environment, and also coarsens upwards (Coleman and Prior, 1982). This is expected in a relatively conformable succession, as the delta front is a higher energy depositional environment than is the prodelta. Variable settling rates between different particle sizes likely caused the graded beds to be deposited. In addition, the increase in bed thickness upwards is consistent with the distal delta front (as well as some other, non-deltaic shorefaces) (Moslow and Pemberton, 1988). The abundance of carbonaceous debris may be indicative of proximity to a river mouth and also seasonal phytodetrital pulses (Rice *et al.*, 1985).

Although the trace fossil assemblage in F2 is more diverse and more abundant than in F1, it still appears to be stressed. Although some burrow types are moderately abundant, most burrow types are rare. This moderate biodiversity is considered to be representative of a river-dominated distal delta front environment similar to that described by Gingras *et al.* (1998).

Facies 3: Interlaminated and Interbedded Siltstone and Sandstone with Very Diverse Trace Fossil Assemblage

*Description*

Facies 3 is present only in the drill cores and is approximately 4.5 m. F3 gradationally or sharply overlies F1, and sharply underlies F4 or F8. Both the lower and upper contact appear to be conformable.

F3 consists of interbedded and interlaminated silt and fine grained sandstone

with rare mud beds and/or laminae. The facies coarsens upward overall. Most of the beds are less than 5 cm thick, and bed thickness commonly increases up-section. Planar parallel bedding, wavy bedding and wave ripples are common. Carbonaceous debris is moderately abundant locally.

*Helminthopsis* and *Chondrites* are very abundant in F3. *Thalassinoides, Planolites, Schaubcylindrichnus, Arenicolites, Ophiomorpha* and *Teichichnus* (Fig. 2.3D) are moderately abundant. *Rhizocorallium, Lockeia, Asterosoma*, and possible *Paleophycus* are locally present in F3. The trace fossil assemblage is more diverse, more abundant, and more regularly and evenly distributed in F3 than in F2. In addition, the burrows are more robust in F3 than in F2. Overall, there is also more burrowed sediment in F3 than in F2.

*Interpretation*

Facies 3 is interpreted to represent a wave-influenced distal bar (Coleman and Prior, 1981) or wave-influenced distal delta front (Reading and Collinson, 1996) environment (fig. 2.2).

The distal delta front commonly contains ichnogenera similar to those expected in the upper offshore to lower shoreface environment of non-deltaic environments (MacEachern, 2000). A diverse *Cruziana* ichnofacies similar to that described by MacEachern and Pemberton (1992) is present. This assemblage is similar to the wave-dominated trace fossil assemblage described by Gingras *et al.* (1998) in the Dunvegan Formation.

It is possible that the increased number of trace fossils in the drill cores is due to the better preservation of the biogenic sedimentary structures in the drill cores (i.e the structures are easier to see). However, the outcrops occupy a small depositional area within the greater study area. As such, the variability in trace fossil abundance is interpreted to indicate variable environmental conditions along a coastline that was

caused by mechanisms such as abandonment or shifting of deltaic lobes, or avulsing distributary channels (Moslow and Pemberton, 1988).

Facies 4: Hummocky to Swaley Cross-Stratified Sandstone (Fig. 2.5)

*Description*

The apparent thickness of Facies 4 (F4) ranges from approximately 2-7 m with an average of 4.7 m. F4 is present throughout most of the study area, except in the far northwest. F4 has either an abrupt or gradational lower contact. Where a gradational contact is present, the predominantly sandstone unit contains up to 15 cm of interbedded mud and silt at the base. The contact appears to be both flat-lying and conformable throughout the outcrop study area, and is sometimes marked by a prominent siderite horizon. F4 erosionally underlies Facies 5 (F5), or sharply underlies F8 or F9. The F4-F5 contact is commonly marked by a sideritized sandstone or sideritic clast bed that ranges in thickness from 5 cm to 1.2 m. The bed tends to be thicker at locations where the contact is marked by clasts than where it is marked by a sideritized sandstone. The clasts found along the contact range from well rounded to jagged, and appear to lie on the bedding planes. The upper contact is commonly wavy, reflecting the topography of the bedding. Also, F4 commonly grades laterally into F8.

F4 is either recessive or prominent. The prominent sections are manifested as hoodoos or cliffs. Where recessive, F4 consists of a coarsening upward, grey or yellow sandstone. Where prominent, both blocky and coarsening upward grey or yellow sandstones are observed. Grain size at the base of the unit ranges from lower very fine to fine grained sandstone, whereas grain size near the top of the unit ranges from upper fine to upper medium grained sandstone. The grain size commonly increases rapidly in the basal 0.5-1 m, and more gradually throughout the remainder

Figure 2.5. Proximal delta front deposits (F4) in outcrop and drill cores. F4 in these photos belongs to FA1.

A. Sharp contact between F2 and the overlying F4 at EC-B. Hammer is 38 cm long. The F2-F4 is commonly quite sharp, and thus is easy to recognize, even from a distance.

B. Hummocky cross-stratification in outcrop at EC-N. Note the characteristic upward curvature of the hummock and low angle intersections of the laminae and beds.

C. Hummocky cross-stratification in drill core at 1-24-28-19W4 at approximately 152 m.

D. Coaly debris draping the bedding planes at EC-H. Scale bar is 15 cm long.

A.
B.
C.
D.
Contact

of the unit. Occurrences in the northwest portion of the outcrops are generally coarser grained. Sideritized sandstone beds are commonly observed.

Although planar to low angle inclined bedding is locally visible at the base of this unit, F4 is characterized by hummocky or swaley cross stratification. The planar to low angle inclined bedded interval is typically less than 0.5 m thick, with individual beds averaging approximately 4 mm in thickness. The hummocky cross stratified beds range in thickness from 6-8 mm to 1.5-2 cm, with bed thickness increasing upwards. The bedding structures are commonly well preserved in both the previously mentioned hoodoos, and also within large boulder-like concretions that occur within the facies. However, bedding structures can still be discerned in the surrounding, more recessive rocks. The boulders commonly contain siderite clasts that range in size from 0.5 cm-5 cm.

Interlaminated sand, mud and coal, and coal pods and coal layers are visible locally. Where present, the muddy laminae typically occur near the very base of the unit. These mud stringers are discontinuous, averaging about 10-15 cm in length and 1-2 cm in thickness. The pods of carbonaceous debris are typically a few centimeters in size. Coaly debris layers typically lay along the bedding planes. F4 is devoid of bioturbation.

Figure 2.9B shows an isopach of F1, F2, F3 and F4. These facies when considered together appear to thicken towards the southeast. In addition, a deflection in the contours towards the southeast can be seen in the middle portions of the study area.

*Interpretation*

Facies 4 is interpreted to represent storm reworked distributary mouth bar (proximal delta front) deposits (Coleman and Prior, 1982 and Reading and Collinson, 1996) (Fig. 2.2), or storm dominated lower shoreface deposits (Fig. 2.6). As noted by

Coleman and Prior (1982), distributary mouth bars at the mouths of individual distributaries commonly merge to form a nearly continuous strip of sand around the periphery of the delta. This depositional environment occupies much the same depositional position as the lower shoreface, and as such, can have similar characteristics.

Some controversy surrounds the processes involved in the formation of hummocky and swaley cross-bedding, however there is general consensus that the bedforms develop during storms (Duke *et al.*, 1991; Leckie and Walker, 1982 and Johnson and Baldwin, 1996). The complete lack of bioturbation is likely due to the extremely high energy conditions that were either not able to support life, or that prevented the preservation of trace fossils. MacEachern and Pemberton (1992) indicated that although storm-dominated sediments commonly have some bioturbation, it is not unusual for some intervals to lack evidence of biogenic activity.

The presence of coaly debris is likely due to proximity to a fluvial point source. The rare muddy laminae may be the result of post-storm fallout of fine grained materials (Massari and Parea, 1988).

The overall thickening towards the southeast in figure 2.9B is to be expected as the southeasterly outcrops contain some deeper water facies than the northwesterly outcrops, and as such, the paleo-basinward direction appears to be towards southeast.

Facies 5: Blocky to Fining Upward Trough Cross-Stratified Sandstone (Fig. 2.7 & 2.8)

*Description*

The apparent thickness of F5 ranges from 2-9.2 m with an average of 5.4 m. F5 is present throughout the study area, except in the northwesterly portion. This facies erosionally overlies F4. F5 conformably underlies Facies 6 (F6). The F5-F6 contact is most commonly sharp, but is locally gradational. The contact between F4

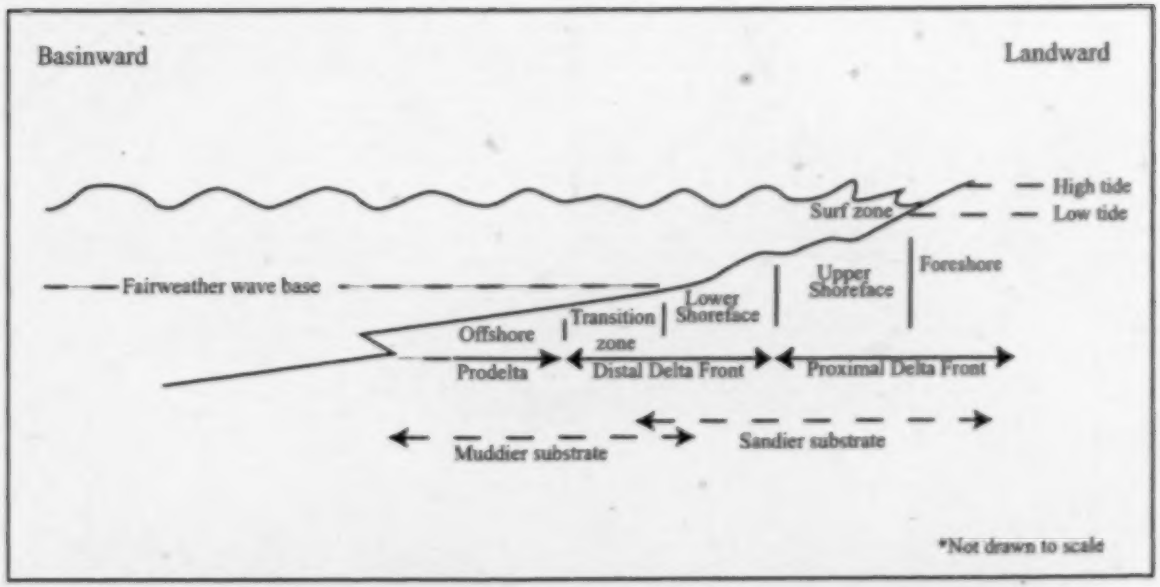



Figure 2.6. Schematic diagram comparing the environments present on a barrier island or strandplain with those environments present in a delta. Modified after Moslow and Pemberton (1988) and Walker and Plint (1992).

Figure 2.7. Distributary channel deposits (F5) in outcrop. F5 in these photos belongs to FA1.

A. Prominent trough cross-bedded sandstone from a distance at EC-A.

B. Clasts at the base of F5, marking the F4-F5 contact at EC-G. Ice axe is 74 cm long. The bed containing the angular to rounded clasts ranges between 0.5-1.2 m thick.

C. Muddy laminae and carbonaceous debris laminae in the upper portions of F5 at EC-H. Pencil is 14.5 cm long. The muddy laminae and carbonaceous debris laminae are more prevalent in the northwesterly outcrops.

D. Single *Planolites*? (*Pl*) in a mud clast in the upper portions of F5 at EC-H. Pencil is 14.5 cm long. Burrow traces are extremely rare in this facies.

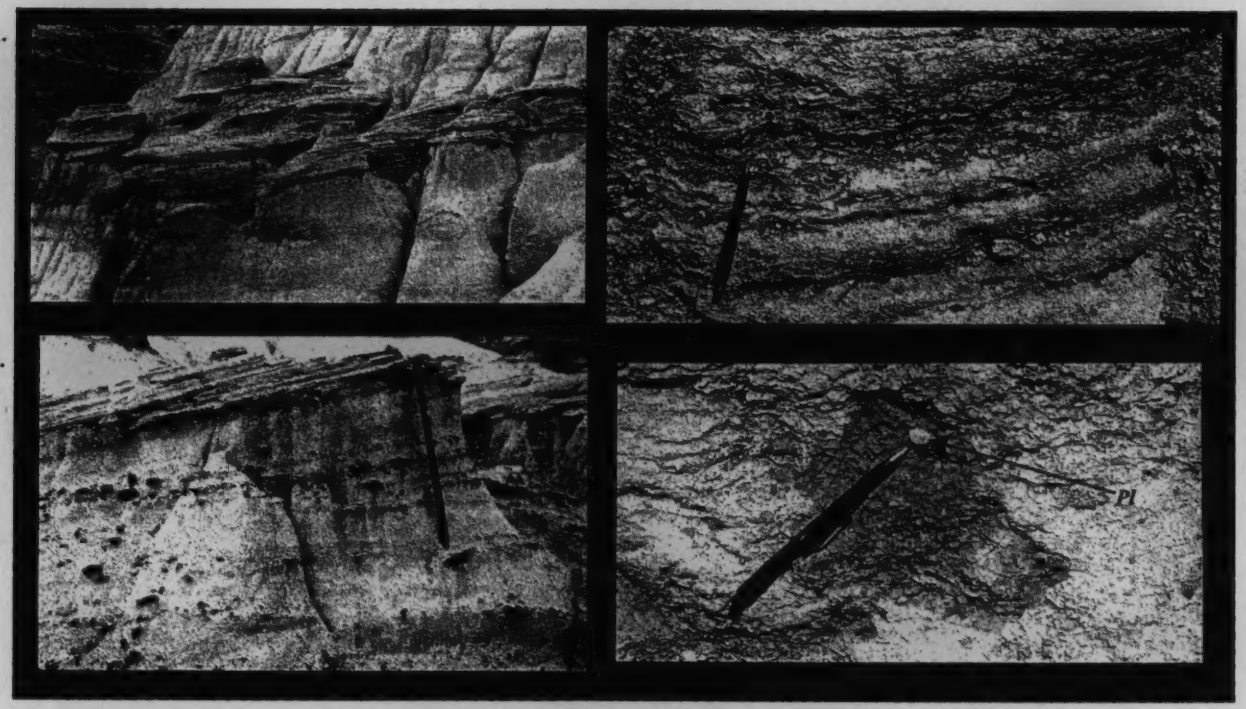

A.
C.
B.
D.
PI

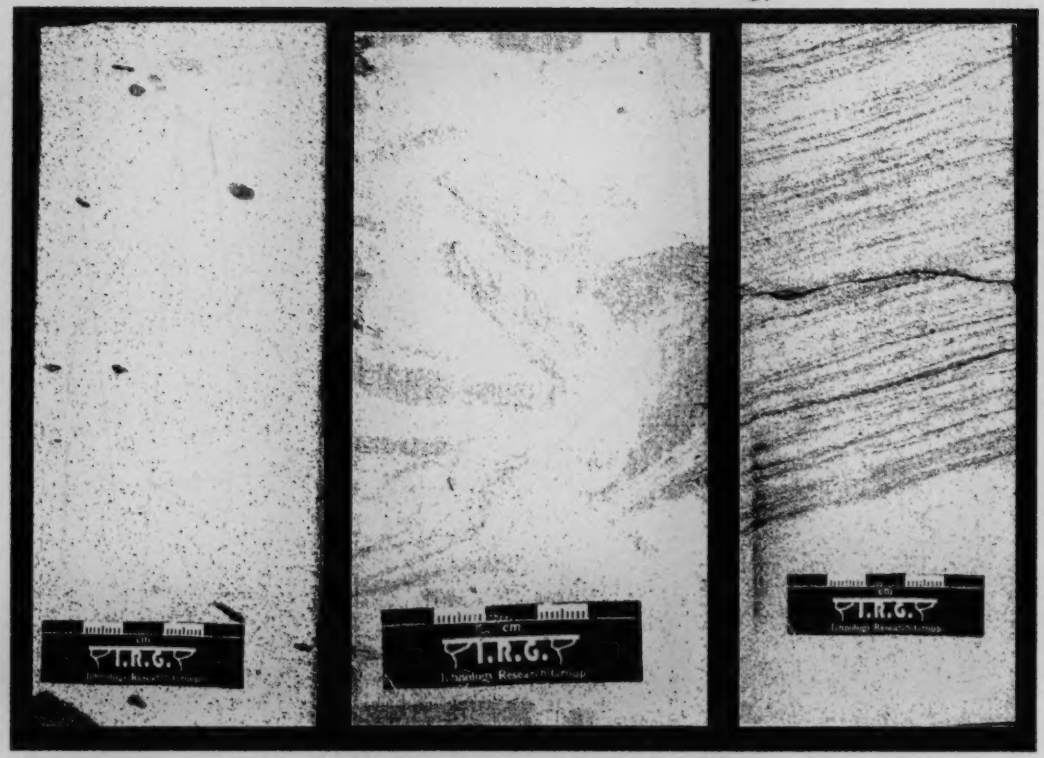
Figure 2.8. Distributary channel deposits (F5) in drill cores. F5 in these photos belongs to FA1.

A. 1-24-28-19W4 at approximately 120 m. Sideritized and non-sideritized, rounded and angular rip-up clasts in the sandy channel fill. Although rip-up clasts are most prevalent at the F4-F5 contact, rare clasts are dispersed throughout the facies in the drill cores.

B. 1-24-28-19W4 at approximately 113 m. Mud rip-up clasts in the upper portion of F5. No burrow traces are present in the mud clasts in the core, likely because few organisms could survive the stressful, high energy conditions.

C. 1-24-28-19W4 at approximately 110 m. Double mud drapes in the upper portions of F5.

A. B. C.



and F5 is regularly marked by a sideritized sandstone horizon, or by sideritic, angular to well rounded clasts in a bed that ranges in thickness from 0.05-1.2 m (Fig. 2.7B). In drill cores, sporadically distributed mud clasts are present throughout the facies (Fig. 2.8B). The F5-F6 contact is locally marked by a layer of sideritized cobbles that is approximately 10 cm thick.

F5 is recessive overall, but contains hoodoos and some prominently bedded intervals. The abundance of prominent structures in the unit decreases upwards. The unit is sideritized locally, but much less so than F1, F2 and F4.

This mostly grey to yellow sandstone is typically blocky or upwards fining, with rare upward coarsening trends. Where fining upward, the grain size ranges from fine to lower medium sand at the base of the unit to upper very fine sand at the top of the unit. Where coarsening upward, the grain size increases from lower fine to upper medium. Sorting improves up section in most of the outcrops.

Large scale trough cross stratification is common throughout the facies (Fig. 2.7A). Rare tabular cross stratification is present locally. The basal portion of the unit often appears massively bedded. The bed thickness ranges between 0.5-2 cm. Planar horizontal beds between 0.2-0.5 cm on average are locally observed in the uppermost 1 m of the facies.

Muddy laminae, laminae draped with carbonaceous debris (Fig. 2.7C), and coaly pods are present to varying degrees. There is a tendency towards an increased frequency of mud laminae in the upper portion of the unit. In drill cores and rare outcrops, muddy laminae may be grouped together as double mud drapes (Fig. 2.8C). The double mud drapes are not pervasive in the facies, though. Discrete mud beds are also present and may contain sand lenses. The prevalence of the muddy laminae and beds increases toward the northwest. In addition, mud clasts approximately 1-2 cm in size are sometimes associated with these laminae. Pods of well rounded mud clasts

averaging 1 cm in size are not uncommon in the upper portions of the unit.

Carbonaceous debris laminae are commonly viewed in the basal to middle portion of the facies, with the carbonaceous debris commonly draping the foresets of the beds. The carbonaceous laminae tend to be discontinuous and typically a few mm thick. Groups of laminae are rarely thicker than 5 cm or 6 cm. In addition, the carbonaceous laminae are up to 5 m long and approximately 1-3 cm thick. These laminae tend to occur in groups of 4 or 5, but are not pervasive throughout the facies. In the southeast, the carbonaceous laminae tend to be more discontinuous, rarely longer than 5 cm, and do not repeat. Convolute laminae are common in the upper portion of the facies, as are small (10-20 cm or less) flame structures.

Paleocurrent measurements of the trough and tabular cross bedding indicate a dominant flow direction of 90-180 degrees, or towards the southeast. However, good 3-dimensional exposures of bedding structures are not abundant in the outcrops studied.

The only bioturbation observed in F5 are sand-filled burrow traces approximately 1 cm in diameter within the previously mentioned mud clasts observed associated with the muddy and carbonaceous stringers (Fig. 2.7D). These burrows may be *Planolites*, and are extremely rare.

Maps of the location of F5 display a branching morphology (Fig. 2.9). It is discontinuous throughout the study area in both drill cores and outcrops lending an uncertainty to its spatial distribution.

*Interpretation*

Facies 5 is interpreted to represent a deltaic distributary channel system (fig. 2.2) that experienced some estuary-like conditions such as tides and possibly brackish waters.

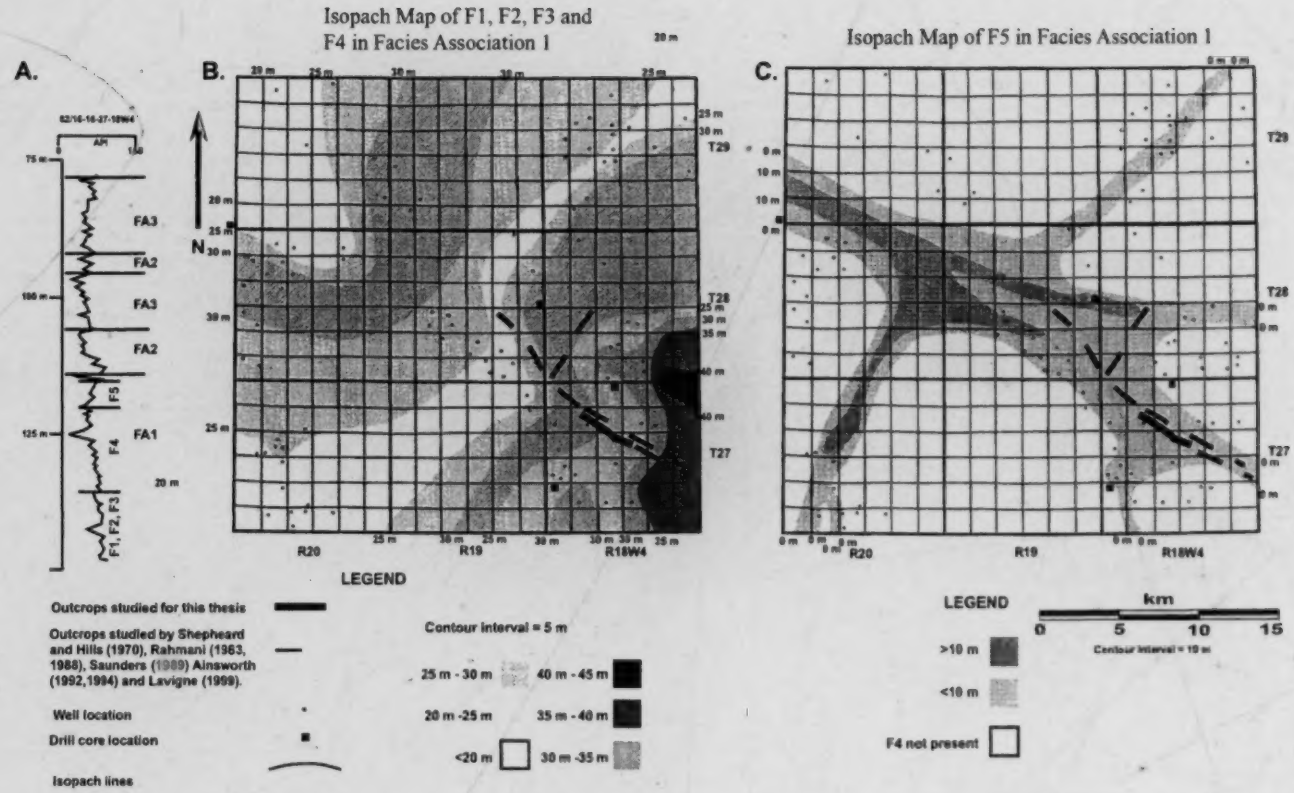
The blocky to fining upward grain size trend, and erosional base demar-

Figure 2.9. Facies distributions in the "EC" delta lobe.

A. Representative geophysical well log showing relative stratigraphic placement of the facies associations present. Note the stratigraphic position of F1-F5 in FA1.

B. Isopach map of F1, F2, F3 and F4 (the prodelta and delta front) in FA1. Note that there is a slight "thinning" where these facies underly the thicker portions of F5. This indicates possible erosion of the facies by F5.

C. Isopach map of F5 in FA1. Note that F5 is not present in all locations, so its spatial distribution is open to question.


A.
B.
C.
Isopach Map of F1, F2, F3 and F4 in Facies Association 1
Isopach Map of F5 in Facies Association 1
FA3
FA2
FA3
FA2
FA1
F5
F4
F1, F2, F3
N
T29
T28
T27
R20
R19
R18W4
LEGEND
Outcrops studied for this thesis
Outcrops studied by Shepheard and Hills (1970), Rahmani (1963, 1988), Saunders (1989) Ainsworth (1992,1994) and Lavigne (1999).
Well location
Drill core location
Isopach lines
Contour interval = 5 m
25 m - 30 m
40 m - 45 m
20 m -25 m
35 m - 40 m
<20 m
30 m -35 m
LEGEND
km
0 5 10 15
>10 m
<10 m
F4 not present

cated by rip-up clasts are common features of channel deposits (Reineck and Singh, 1973; Miall, 1992 and Boggs, 1995). The fining upward trend is likely the result of point bar migration due to the meandering nature of the distributary channels, which is noted in a number of modern deltaic distributaries (Coleman and Prior, 1982). Although most distributary channels tend to be stable, tidal influence is indicated by Coleman and Prior (1982) to lead to more migratory channels. In addition, most of the channel deposits comprising F5 only scour into the delta front sands, not the prodelta clays and muds. As such, the channel flow paths are not as confined as they might otherwise be. The portions of F5 with the more blocky grain size trends or the very rare coarsening upward trends may have experienced some reworking by marine processes. It is also possible that the blocky grain size trend indicates a small range of available grain sizes in certain portions of the delta.

Trough cross-bedding is shown to be common in most types of channels (Bhattacharya and Walker, 1991; Reinson, 1992 and Collinson, 1996), including delta distributary channels (Reading and Collinson, 1996). The parallel bedded sandstones seen in the upper portion of F5 are interpreted to represent upper flow regime conditions. Collinson (1996) indicated that these parallel bedded sandstones can be found anywhere within a channel, but are most common near the top.

Muddy laminae, carbonaceous debris, mud clasts and slumping features are also common to most types of channels (Coleman, 1976; Reinson, 1992 and Boggs, 1995). The muddy laminae are most common in the upper portion of the facies, as they were likely the smallest particles present and were deposited during waning conditions. The carbonaceous debris originated from plant and organic material that was broken up and transported downstream, possibly during floods. The mud rip-up clasts and slumping features are the result of undercutting of the river bank by the channel itself during channel migration.

The double mud drapes present in the drill cores indicate tidal influence (Nio and Yang, 1991), and marine conditions. However, a dominant southeasterly flow direction is indicated by the trough and tabular cross-bedding in the outcrops, with no evidence of a subordinate or second current flow direction. As such, it is believed that the degree of tidal influence was variable throughout the area.

Figure 2.9C shows the typical branching pattern of a distributary channel system. Also note, that the presence of F5 is commonly associated with a "thinning" of the isopach of F1, F2, F3 and F4 (Fig. 2.9B). As such, F5 likely eroded into the delta front to varying degrees.

Facies 6: Interlaminated and Interbedded Mudstone, Siltstone, and Sandstone

*Description*

The apparent thickness of Facies 6 (F6) (Fig. 2.10) ranges from approximately 0.2-11 m with an average of approximately 3 m, but is typically thicker in the northwest. F6 is present throughout the study area, and has either a sharp or gradational lower contact that is marked by a bed of siderite cobbles locally. There is no evidence for significant erosion at the basal contact. The upper contact is typically sharp, but conformable.

Most of the unit is grey and brown, with orange coloration where minor sideritization occurred. F6 is mostly recessive in nature and commonly weathered and friable. The weathered, friable nature may obscure any sedimentary structures.

F6 consists of delicately interlaminated and interbedded mud, silt, very fine, and fine grained sandstone. However, the facies contains some apparently massive intervals of mud, silty mud or sandstone. Most beds are less than 1 cm thick, with most laminae being approximately 1 mm to 2 mm thick. The unit commonly demonstrates an overall fining upward profile of interlaminated mud and lower fine

Figure 2.10. Interdistributary bay fill deposits (F6) in outcrop at EC-K. F6 in these photos belongs to FA1.

A. Small scale ball and pillow structure. Scale bar is 15 cm long. Note that the friable nature of F6 often makes physical and biogenic sedimentary structures difficult to see.

B. Synaeresis cracks and possible *Planolites*. Scale bar is 15 cm long.

C. Asymmetrical wave ripples and possible root casts (in the white box). Approximately 8 cm of the pencil is showing.

A.
B.
C.
Ripples

grained sandstone to interlaminated mudstone, siltstone and lower very fine grained sandstone. Repeating fining upward profiles a few cm thick are common. Rare, 1 cm thick repeating coarsening upward beds are also present. Most of the beds and laminae are planar, but wave rippled laminae are also observed. Asymmetrical ripples, which are present locally (Fig. 2.10C), have an average wavelength of approximately 10 cm and an average amplitude of 0.2 mm-0.5 mm.

Sporadically distributed, tiny carbonaceous debris are present in this unit. Some small synaeresis cracks (Fig. 2.10B) (around 1 cm long and a few mm across) are observed on occasion, as well as some possible tiny *Planolites*, up to a few mm in diameter. In addition, some tiny ball and pillow structures (Fig. 2.10A) and possible root casts (Fig. 2.10C) are noted.

*Interpretation*

Facies 6 is interpreted to represent interdistributary bay (Fig. 2.2) and lagoonal deposits. Sediments deposited in these two depositional environments commonly exhibit similar characteristics. As such, they are differentiated from one another primarily by their facies associations. The interdistributary bay deposits are associated with deltaic strata, and represent coastal plain deposition. The lagoonal rocks are associated with both transgressive shoreline deposits, and protected bay deposits. The lagoonal deposits in the outcrops also tend to be thinner than the interdistributary bay deposits in the outcrops, and display sharp contacts more often.

The mostly delicately interlaminated fine grained sediments with ripples indicate mostly quiescent conditions. However, since much of F6 is unconsolidated, it is difficult to identify many sedimentary structures. The synaeresis cracks indicate salinity fluctuations and some degree of brackish conditions which are common to both environments.

The presence of *Planolites* indicates the presence of some tiny burrow-

ing organisms. These occurrences typically indicate some small degree of marine influence (Pemberton and Wightman, 1992), as would be found in coastal plain or lagoonal settings. However, the paucity and low diversity of trace fossils indicates hostile living conditions, such as low (and fluctuating) salinity (Pemberton and Wightman, 1992). As well, burrowing is generally reduced in interdistributary bays that experience rapid deposition (Coleman and Prior, 1981). The ball and pillow structures indicate some localized rapid deposition (Reineck and Singh, 1973), and the root casts indicate some areas of plant growth and potentially subaerial exposure.

Facies 7: Coal Seams and Large Coal Lenses (Fig. 2.11)

*Description*

F7 ranges in apparent thickness from approximately 0.1-0.67 m, with an average of 0.44 m. F7 recurs throughout the study area and the stratigraphic interval. Regardless of the overlying or underlying facies, the contact is usually sharp, although some gradational lower contacts are observed.

F7 consists of dark grey to black coal seams and coal lenses. Much of the facies is weathered and slumped. In some places, the coal is associated with brown, muddy, carbonaceous shale, or sideritic, fine grained sediment.

*Teredolites* is observed in the top of some of the coal seams and pods in beds averaging approximately 5 cm thick (Fig. 2.11A & B). These burrow traces are filled with upper very fine to lower fine grained sand or mud, and are commonly sideritized. The burrow diameter ranges from approximately 0.5 cm to 3 cm.

*Interpretation*

Facies 7 is interpreted to represent a coastal swamp or marsh environment. A significant vegetated community developed, and then experienced low detrital influx. A relatively high water table would have been required to coalify the vegetation (Gal-

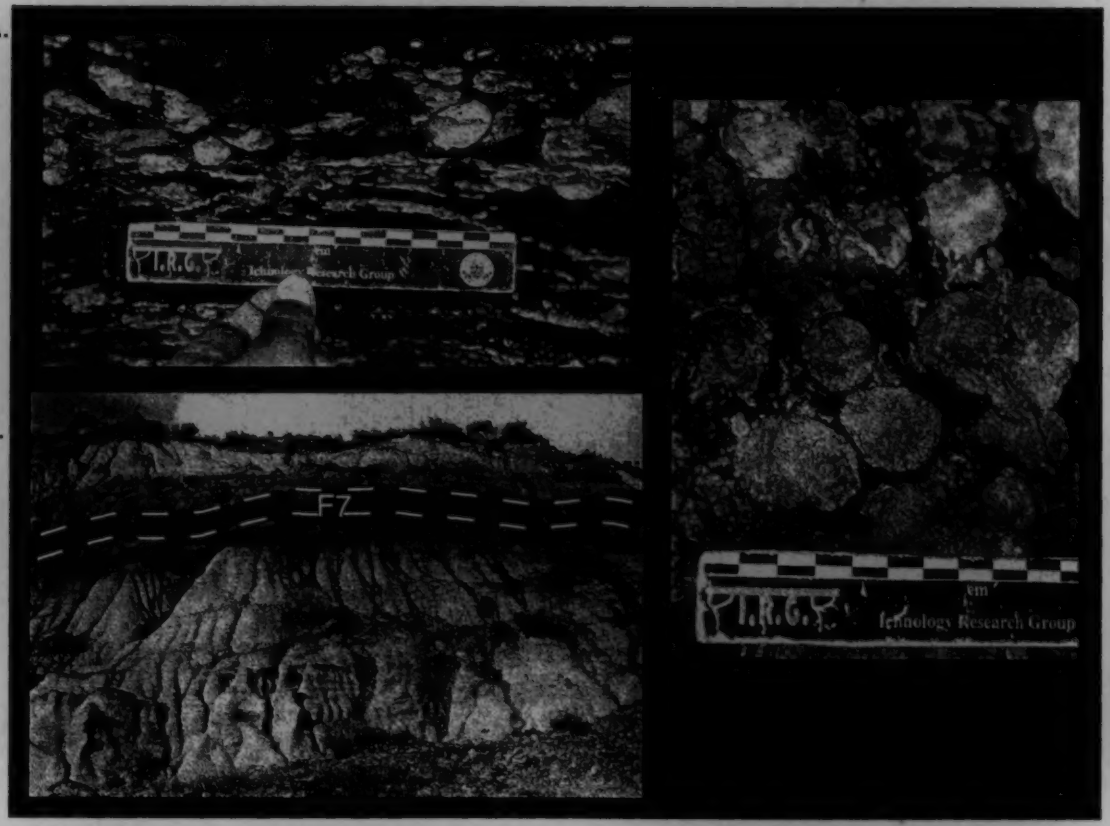
Facies 2.11. Swamp or marsh deposits (F7) in outcrop.

A. Cross-section of sand-filled *Teredolites* in the top of a coal seam in FA4 at EC-H.

B. Looking up at the base of a bed of sand-filled *Teredolites* in the top of F7 in FA4 at EC-H.

C. View of F7 in FA3 in outcrop at EC-E.

A.




B.

C.

loway and Hobday, 1996).

The *Teredolites* indicates that more marine conditions followed the development of the swampy or marshy environments, as these burrow traces are thought to represent marine bivalve wood borings. (Bromley *et al.*, 1984 and Lavigne, 1999).

Facies 8: Blocky to Coarsening Upward Sandstone with Abundant *Ophiomorpha* (Fig. 2.12 & 2.13)

*Description*

Facies 8 (F8) averages approximately 3 m in apparent thickness. F8 typically has sharp, and conformable lower and upper contacts. Also, F8 commonly grades laterally in F4. This facies consists of brown to grey, blocky to coarsening upward very fine to fine grained sandstone. F8 is comprised of both recessive and prominent sediments. Lichens sometimes covered the more prominent deposits. Siderite is present, but rare in this unit. Although visible bedding structures are rare, some planar bedding occurs locally within the unit, typically near the top of the facies. In addition, planar, parallel shale laminae are present in limited abundances. Very rare, tiny carbonaceous debris also occur. Where present, the carbonaceous debris is typically concentrated into discontinuous laminae.

This facies is typically moderately to pervasively bioturbated, containing mostly *Ophiomorpha borneensis*. In most deposits, the burrows themselves are preserved, however, locally only burrow molds are present. Most of the *Ophiomorpha borneensis* are robust and sideritized (Figs. 2.12 and 2.13) with an average pellet diameter of approximately 0.4 cm. The average length of exposed burrows is about 20 cm, with burrow diameters ranging between 0.4-3 cm. The burrow configurations are variable, but are normally linear or radiating. The burrow systems appear to be predominantly horizontal, with only short vertical shafts. Some portions of the

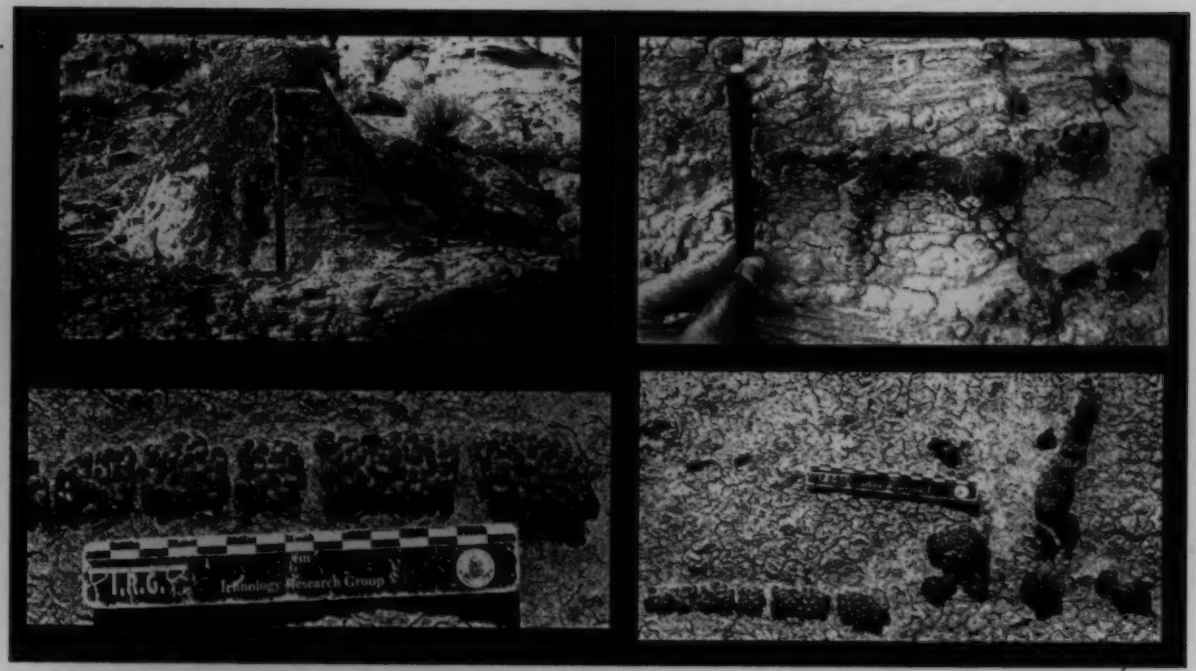
Figure 2.12. Lower to middle shoreface (F8) deposits with abundant *Ophiomorpha borneensis* in outcrop.

A. Sideritized *Ophiomorpha* system in F8 in FA3 at EC-B. Ice axe is 74 cm long. Note that the burrow traces are commonly very hard, and very strong. A high density of burrows may make the facies difficult to erode, as is pictured here.

B. Close-up view of *Ophiomorpha* system in F8 in FA3 at EC-B. Pencil is approximately 14.5 cm long.

C. & D. Close-ups of *Ophiomorpha borneensis* in F8 in FA1 at EC-P. Scale bar is 15 cm long. The burrow traces are less abundant in FA1 than in FA3, but are equally as robust.

A.



B.

C.

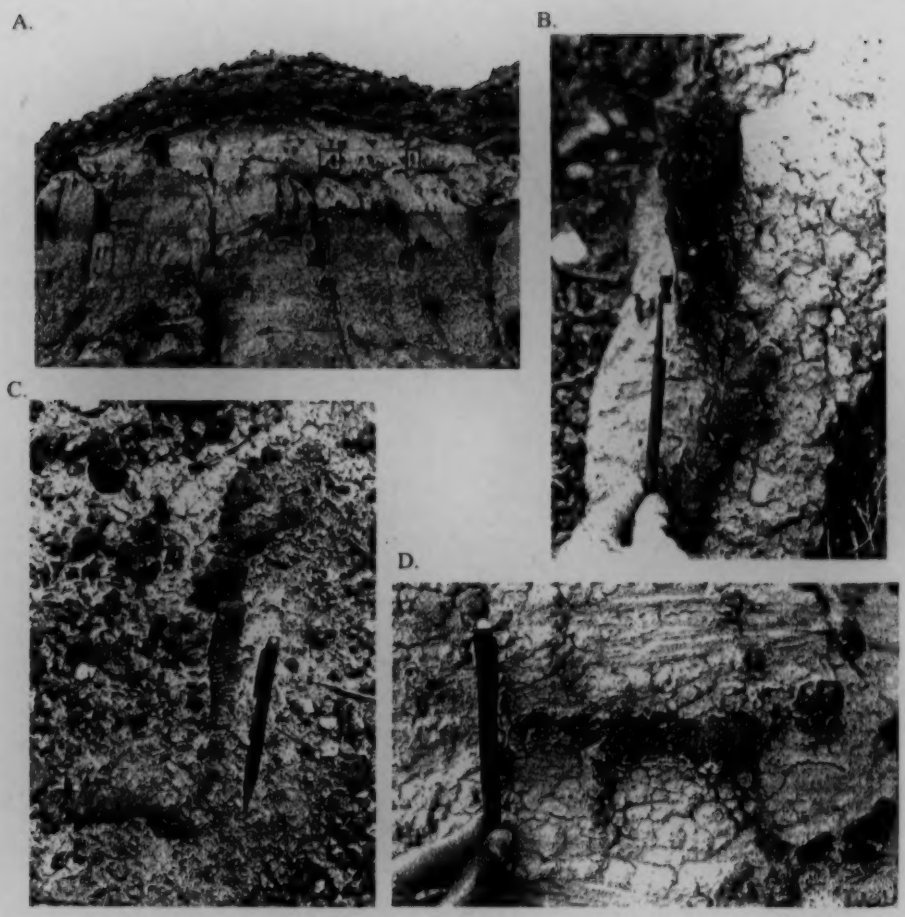
D.

Figure 2.13. Lower to middle shoreface (F8) deposits with abundant *Ophiomorpha borneensis* in outcrop.

A. Sideritized *Ophiomorpha* in FA3 at EC-D Note that the burrow traces (in black boxes) are commonly very hard and more resistant to erosion than the surrounding rock

B. At EC-D, a close-up view of vertical *Ophiomorpha*. Pencil is approximately 14.5 cm long.

C. & D. Close-ups at EC-B of *Ophiomorpha*. Pencil is approximately 14.5 cm long.


A.
B.
C.
D.

burrow system are not pelleted, most commonly the undersides of the burrow traces. Very rarely, this facies contains *Teichichnus*.

*Interpretation*

Facies 8 is interpreted to represent lower to middle shoreface deposits (Fig. 2.6) or proximal delta front deposits (Fig. 2.2). The overall coarsening upward profile of very fine to fine grained sands, as well as the common association with the hummocky to swaley cross-stratified sandstones of F4 is consistent with this environmental setting. Furthermore, *Ophiomorpha* is a common trace fossil in nearshore sands (Frey et al., 1978).

High energy conditions are indicated by the robust burrows designed to withstand constantly shifting substrates. The lack of other biogenic structures suggests a somewhat hostile environment. It is likely that only the tracemakers responsible for the *Ophiomorpha borneensis* could withstand this high energy environment.

There has been much speculation regarding possible modern analogues for the tracemaker responsible for *Ophiomorpha* (Hoyt and Weimer, 1963; Frey *et al*.. 1978 and Pemberton *et al*., 1976). Extant tracemakers including various callianassid, upogebiid and axiid shrimp have been suggested to be possible modern analogues. These types of shrimp make burrows that look similar to *Ophiomorpha*, and appear to live in similar depositional settings to the *Ophiomorpha* tracemaker (see Weimer and Hoyt, 1964; Pemberton et al., 1976 and Frey et al., 1978). At present, however, the identity of the tracemaker responsible for the burrow trace is not known. Further discussion on this topic is found in Appendix I.

Facies 9: Hard, Brown Sandstone with Carbonaceous Rip-Up Clasts and Plant Debris

*Description*

Facies 9 (F9) ranges in apparent thickness from 0.1-1.6 m, with an average of

0.45 m. F9 tends to have both sharp upper and lower contacts. This facies consists of very hard, dark brown, siltstone to medium grained sandstone, with abundant coaly wood clasts and carbonaceous plant debris. The coaly and carbonaceous plant debris ranges in size from a few mm to 5 cm. Planar lamination is noted. In addition, possible rootlets are identified. No bioturbation is observed in F9.

*Interpretation*

Facies 9 is interpreted to represent subaerial natural levee deposits. These types of deposits are commonly composed of silts and sands with plant and other debris (Coleman, 1976). In addition, these deposits are characterized by a variety of physical sedimentary structures (Coleman, 1976), such as planar lamination. The relative hardness of the facies may be due to oxidation. Furthermore, this unit is often overlain by a coal bed that indicates the existence of a swamp or marsh environment laterally adjacent to the facies.

Facies 10: Burrow Mottled Sandstone (Fig. 2.14)

*Description*

Facies 10 typically ranges between 0.5-3 meters in apparent thickness. Both upper and lower contacts tend to be quite sharp. This facies consists of predominantly blocky to coarsening upward sandstone, although a fining upward profile is seen rarely. The grain size ranges from very fine to upper medium sand sized particles. Trough cross-bedding, tabular cross-bedding, and planar bedding are all present, as well as some wave ripples. Carbonaceous debris, and plant and woody debris are present locally.

Bioturbation intensity is variable, ranging from low to high. In many areas, physical sedimentary structures are obscured by the biogenic sedimentary structures.

*Ophiomorpha* is the most common and most abundant trace fossil in F10.

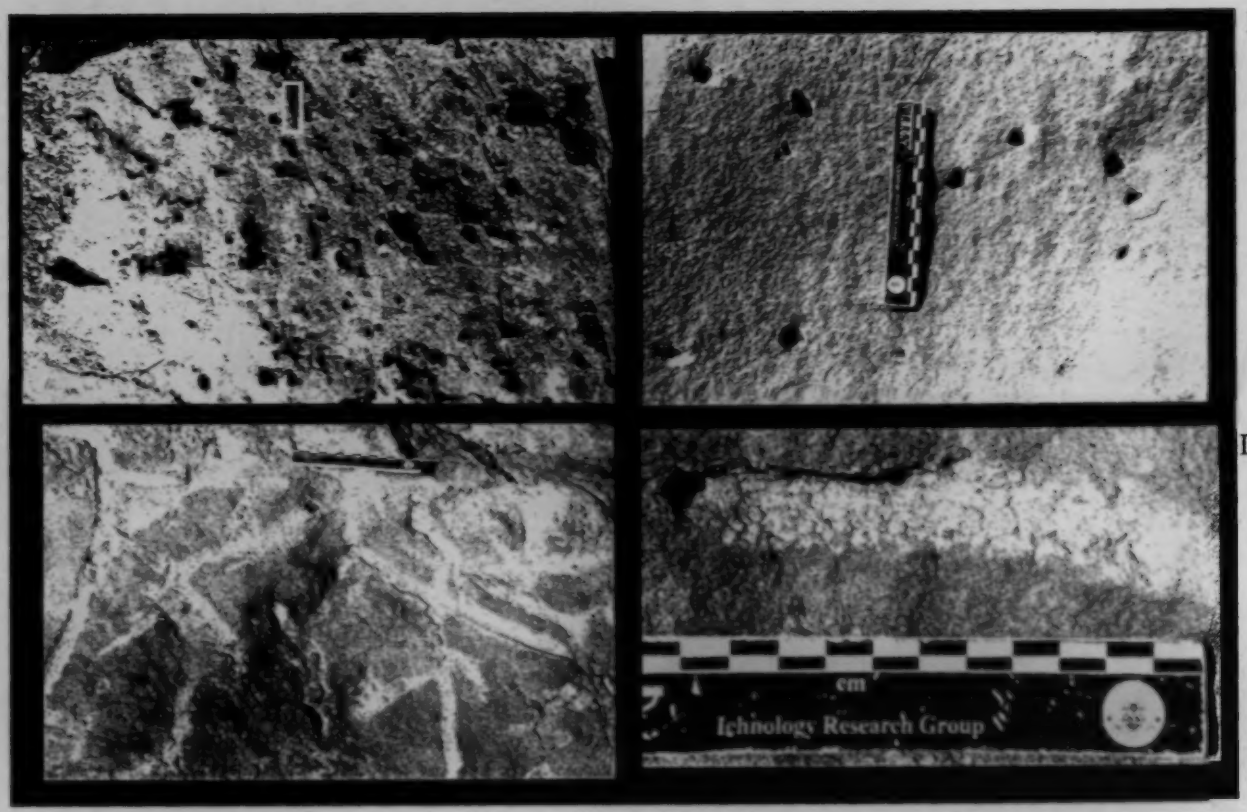
Figure 2.14. Intertidal sand flat (F10) deposits in FA4 at EC-K.

A. Note the high number of burrow apertures that are observed on the top of a bed. Beds such as these are common in F10. Pencil (in small white box) is 14 cm long.

B. Paired burrow apertures. Some of the paired apertures in F10 are pelleted, and some are not. The pelleted aperatures indicate *Ophiomorpha*; the non-pelleted aperatures may or may not indicate *Arenicolites*.

C. Typical view of silicified *Ophiomorpha* system. Note that the scale bar is 15 cm long.

D. Close up view of silicified *Ophiomorpha*.


A.
B.
C.
D.
cm
Ichnology Research Group

Most of the *Ophiomorpha* present in F10 are silicified (Figs. 2.14C & D) and horizontal, with only short vertical shafts. Burrow trace diameter ranges from 0.5 cm to 3 cm. The *Ophiomorpha* are linear, radiating, or even curved. Pellet diameter is a few mm on average.

Other common traces include *Skolithos*, *Paleophycus*, *Arenicolites* and rare *Cylindrichnus* and *Macharonichnus*. Individual deposits of F10 rarely contain more than a few of these traces in any locality. Small scale wave ripples are periodically associated with the burrow traces.

In some locations, the base of the facies is marked by a bed of coal lenses. These coal lenses may contain sand filled *Teredolites*.

*Interpretation*

Facies 10 is interpreted to represent intertidal sand flats. The variability in physical sedimentary structures suggests deposition in this environment as tidal flats are affected by many different processes (Weimer et al., 1982), in this case, mostly waves. The carbonaceous, plant, and woody debris are either indicative of the vegetation that is common to intertidal flats, or of a laterally adjacent vegetated area.

The low diversity trace fossil assemblage is likely due to the many stresses in an intertidal environment, such as extremes in currents and water depths, fluctuating salinity and variable deposition rates. The low burrow trace densities in some areas may be attributed to some of these stresses, especially rapid deposition. High burrow trace density in other areas may be responsible for obscuring other sedimentary structures (Weimer et al., 1982 and Gingras et al., 1999).

Weimer et al. (1982) indicated that there are no physical or biogenic sedimentary structures that are restricted to this facies. Tidal flats are recognized based on their physical characteristics, in combination with their stratigraphic relationships to other facies. F10 is interpreted to represent an intertidal sand flat facies based on its

structures, and also its association with other protected bay deposits such as washover deposits (F11), lagoons (F6) and brackish bay deposits (F12).

### Facies 11: Sandstone with Thin Carbonaceous Debris Laminae and Thin Coal Beds

*Description*

Facies 11 (F11) is prevalent throughout the study area, and ranges in apparent thickness from 0.13-8 m with an average of approximately 3.5 m. F11 has both sharp and gradational upper and lower contacts. F11 is typically recessive in nature, but is locally prominent.

F11 consists of yellow, grey and brown sandstone that ranges in grain size from lower very fine to upper medium sand sized particles. F11 shows fining upward, coarsening upward, and blocky grain size profiles. Most of the sand is planar stratified or massive, however, some wavy bedding is present. In addition, thin muddy beds and laminae are present

Thin coaly beds that rarely exceed 2 cm in thickness and laminae are widespread. These coaly beds and laminae are generally horizontal, planar, and discontinuous. Rare sand lenses are present within the coal beds. Coal lenses, and scattered, tiny carbonaceous debris are also present. In addition, some of the rocks in F11 are sideritized, especially the coaly and muddy beds and laminae. No biogenic sedimentary structures are apparent in F11.

*Interpretation*

Facies 11 is interpreted to represent washover fan deposits. Reinson (1992) states that washover deposits are formed when wind-generated storm surges cut through and spill over barriers. These deposits are commonly lobate or sheet-like, and provide the mechanism for sand transfer into the foredune belt to form back-barrier sand flats. Washover deposits comprise a significant portion of barrier sand

bodies, especially transgressive barriers (Reinson, 1992). In addition, the planar stratification that is observed in F11 is considered to be a dominant sedimentary structure in washover deposits (Reinson, 1992). The coaly beds may have been deposited between storms, and may indicate the contact between successive washover deposits (Hubbard, 1999). The abundance of carbonaceous debris and coal beds indicates proximity to an exposed area such as a swamp or marsh environment.

Facies 12: Striped Mudstone with Rare Sand Beds and Laminae (Fig. 2.15 & 2.16)

*Description*

Facies 12 (F12) ranges in apparent thickness from a few meters to over 10 m with an average of approximately 9 m. F12 often appears to have an erosive base, but has both sharp and gradational upper contacts. Locally, the basal contact is marked by a discontinuous coal seam (F7).

F12 is primarily composed of brown, grey, or orange, often striped mudstone, with minor light grey, fine grained planar sand beds and laminae. In the southeast, some siltstone and very fine sandstone beds are present rarely. Facies 12 also contains rare carbonaceous laminae, tiny carbonaceous debris and sporadic sideritic nodules.

Bioturbation intensity is quite variable in F12. In some locations, no bioturbation is observed. Elsewhere, the facies is intensely bioturbated, with the abundance of bioturbation increasing upwards within the unit. *Teichichnus* is the most common ichnofossil where burrowing is intense (Fig. 2.15). The *Teichichnus* is extremely small, averaging a few mm in diameter.

Diminutive *Planolites* are also present. The *Planolites* are of lesser abundance than the *Teichichnus*. When present, sandstone-filled, *Teredolites* in coal seams or lenses occur along the basal contact. The *Teredolites* are locally sideritized.

Figure 2.15. Quiescent, brackish bay (F12) deposits in FA2 at EC-O.

A-D. Note the abundance of tiny *Teichnichnus (Te)*. Also note the presence of Planolites. The pencil is approximately 14.5 cm long.

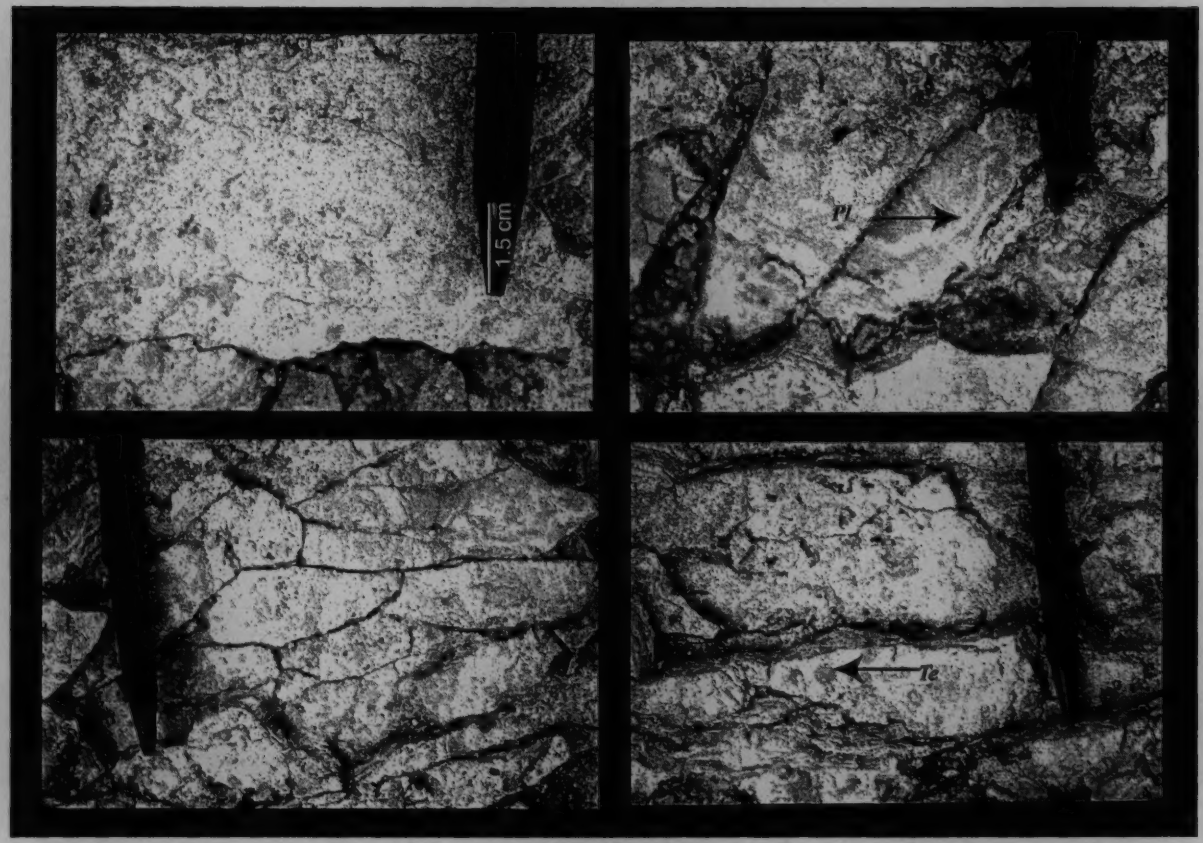

A.
1.5 cm
B.
Pl
C.
D.
Te

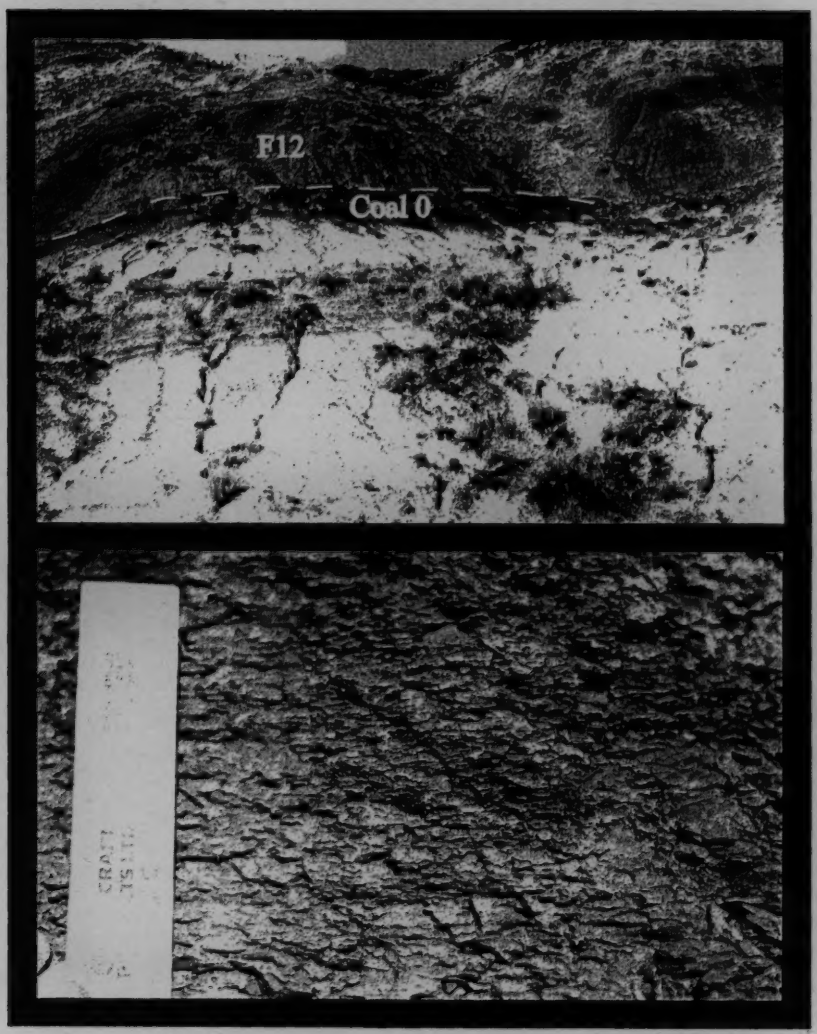
Figure 2.16. Quiescent, brackish bay (F12) deposits.

A. F12 from a distance. At EC-P, F12 is manifested as a muddy channel fill that bottoms out on Coal 0.

B. Close-up of the crumbly, muddy rocks that make up F12 at EC-P. Note that F12 is commonly friable, making physical and biogenic sedimentary structures difficult to identify.

A.

B.



*Interpretation*

Facies 12 is interpreted to represent quiescent, brackish bay deposits. The prevalence of suspension deposited planar laminated mudstones indicates low energy conditions.

The trace fossil assemblage also indicates quiescent, but brackish or marine conditions. The *Teredolites* indicates marine conditions, as the interpreted burrowers (bivalves) live in marine waters (Bromley *et al.*, 1984). The low diversity of, and diminutive sizes of the biogenic sedimentary structures indicate stressful living conditions such as in a brackish water environment (Pemberton and Wightman, 1992). In addition, brackish environments are commonly dominated by a single ichnogenus, sometimes in prolific densities such as is seen with the *Teichichnus* (Pemberton and Wightman, 1992). These depositional settings also tend to be dominated by morphologically simple trace fossils such as the *Teichichnus* and *Planolites* observed in F12 (Pemberton and Wightman, 1992). It is believed that the base of F12 was scoured prior to deposition of the mudstones, and that F12 infilled the topographic depressions.

Facies 13: Thin, Sharp-based Sandstone with Abundant Bioturbation

*Description*

Facies 13 is approximately 1m thick, with a sharp lower contact. F13 typically overlies washover deposits (F11). The upper contact, and overlying unit is covered throughout the study area.

F13 is a fine to medium grained sandstone with a coarsening upward grain size profile. The facies is typically grey or yellowish in color. Some planar parallel bedding and possible wave ripples may be present, but the physical sedimentary structures are generally obliterated by bioturbation. F13 is typically abundantly bio-

turbated with *Thalassinoides*, *Palaeophycus* and *Skolithos*.

*Interpretation*

F13 is interpreted to represent the preserved remnants of a transgressive barrier island. As discussed by Reinson (1992), transgressive barrier islands commonly experience high amounts of wave erosion, and may not be preserved in their entirety, if at all. In fact, only the lagoonal and washover deposits in the transgressive barrier island system may be preserved. Only thin parts of the barrier, such as F13, will pass into the rock record.

The trace fossil assemblage indicates marine deposition. The sharp lower contact may indicate the presence of a transgressive surface of erosion. This interpretation is also supported by F13's association with other transgressive deposits such as washover deposits, quiescent brackish bay fills and lagoons.

Facies 14: Bioturbated Sandstone with Horizontal to Low Angle Inclined Bedding (Fig. 2.17)

*Description*

Facies 14 (F14) ranges in apparent thickness from approximately 2-10 m with an average of approximately 5 m. F14 has either a gradational or sharp lower contact, and a sharp upper contact. This facies is typically a prominent cliff-forming and hoodoo-forming unit composed of yellow, grey and brown sandstone. F14 is either blocky or coarsening upward, ranging in grain size from lower fine to upper medium grained sandstone. The unit is typically well sorted. Sideritization occurs locally. Tiny carbonaceous debris are locally scattered throughout the unit. F14 is commonly covered with lichens.

Although some of this unit appears massively bedded, horizontal to low angle inclined bedding is more common. In many cases, large holes are visible that may

Figure 2.17. Upper shoreface to foreshore (F14) deposits in FA3 observed in outcrop.

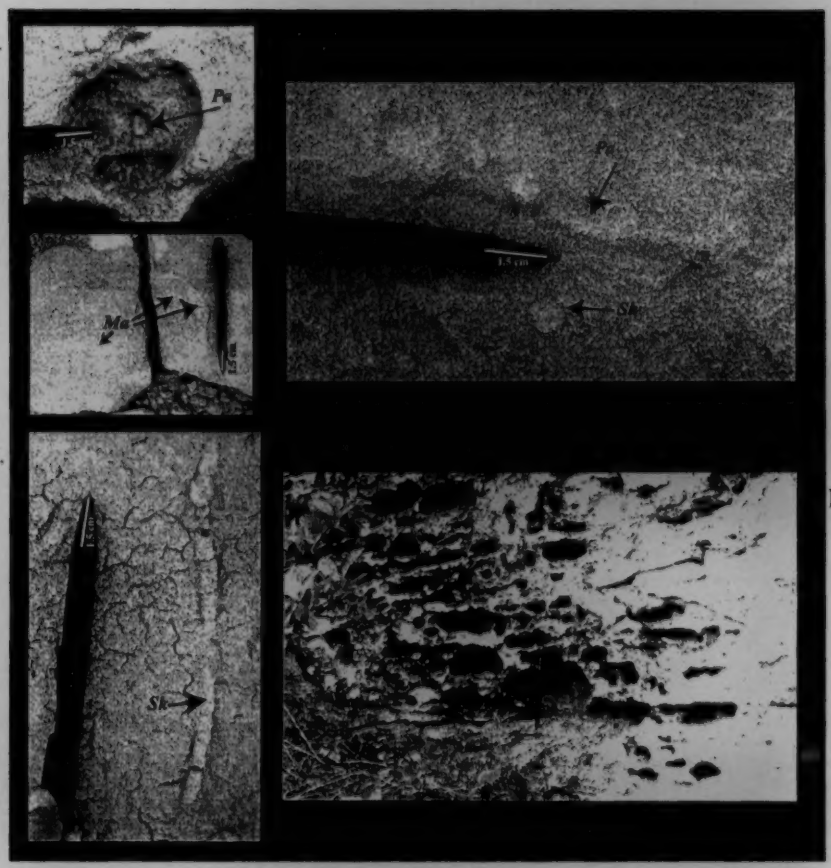
A. *Palaeophycus (Pa)* at EC-A. Note the distinctive lining of the burrow trace that differentiates *Palaeophycus* from other similar burrow traces such as *Planolites*.

B. At EC-B, sparse *Macaronichnus (Ma)*. The abundance of *Macaronichnus* is variable from location to location.

C. At EC-B, side view of *Skolithos (Sk)*.

D. At EC-A, top view of *Palaeophycus (Pa)* and *Skolithos (Sk)*.

E. Large holes commonly observed in F14 at EC-A. These may represent weathered beach pits as described by Davis (1965).


A.
B.
C.
D.
E.
Pe
Ma
Sk
1.5 cm

represent beach pits (Davis, 1965) (Fig. 2.17E).

Bioturbation is typically of low intensity and diversity. *Palaeophycus* is of low abundance, with a usual burrow trace diameter of 0.5 cm or less (Fig. 2.17A). Also of low abundance is *Skolithos* (Fig. 2.17C). The *Skolithos* also has an average diameter of 0.5 cm or less. *Arenicolites* is very rare. *Arenicolites* is interpreted to be present due to the presence of paired apertures visible on the bedding plane. The U-shaped portion of the burrow is not observed. In addition, *Thalassinoides* is rarely present. *Thalassinoides* are typically about 1 cm in diameter, and can be traced for about 20 cm. Only a few imprints of *Ophiomorpha* are seen, and they are typically no more than 1 cm in diameter, and only a few cm long.

*Macaronichnus*, where present, ranged from sparse (Fig. 2.17B), to abundant and pervasive. The burrows ranged from short and linear, to longer and sinuous, or even circular. The *Macaronichnus* is always observed in thin, monospecific beds.

*Interpretation*

Facies 14 is interpreted to represent upper shoreface to foreshore deposits (Fig. 2.6). The transition from the lower to middle shoreface deposits (F4 or F8) into F14 is typically noted by a change to predominantly low angle or parallel lamination, an increase in grain size, and a decrease in trace fossil intensity.

The horizontal to low angle parallel laminae are believed to have been deposited by the swash and backwash of breakers (Davis, 1985; Prothero and Schwab, 1996). Fine, even laminae are deposited as water flows landward, and then returns seaward (Prothero and Schwab, 1996). The laminae tend to be broadly lenticular, and dip seaward at the angle of the beach slope, which is so shallow in the Horseshoe Canyon Formation as to appear almost horizontal.

Grain size is typically coarser in the upper shoreface and foreshore than it is further offshore, as wave energy tends to be greater (Prothero and Schwab, 1996). As

such, the waves can carry and redistribute larger, heavier particles.

MacEachern and Pemberton (1992) indicated that low abundance, low diversity trace fossil assemblages are common in the upper shoreface and foreshore environments. These environments experience harsh environmental conditions including oxygenation variations and constantly shifting substrates. Ichnofossils also have a low preservation potential, partially due to the high energy conditions.

A dominantly *Skolithos* ichnofacies is present, with mostly vertical to inclined dwelling structures. This ichnofacies typically indicates high energy marine conditions, with shifting substrates, such as is seen in the shoreface to foreshore (Pemberton et al., 1992).

*Macaronichnus* is also quite common in the upper shoreface to foreshore, as the tracemaker appears to be uniquely adapted to the harsh environment. *Macaronichnus* has not been formally classified with regards to the ichnofacies concept, however. The tracemaker responsible for *Macaronichnus* is believed to escape the high energy conditions by burrowing into the substrate (up to several meters below the sediment water interface) (MacEachern and Pemberton, 1992 and Schmidt, 2002). The tracemaker of *Macaronichnus* has been likened to a modern Pacific Coast bloodworm, *Euzonus mucronata*, this bloodworm appears to occupy similar environments and appears to have adopted some similar feeding strategies (Saunders, 1989).

**Facies Associations**

The facies are grouped into four facies associations (see Figs. 2.18 and 2.19). Since the facies have been described in non-genetic terms, a number of the facies have more than one interpretation and are present in more than one facies association,

Facies association 1 (FA1) consists of F1-F8, and is interpreted to represent deltaic deposits. The facies present represent a complete succession of prodelta

| Facies Association | Facies | Description | Interpretation |
|---|---|---|---|
| FA1- Deltaic deposits | F1 | Interlaminated & interbedded mudstone and siltstone with moderately abundant *Helminthopsis* | prodelta |
| | F2 | Interlaminated & interbedded siltstone and sandstone with moderately diverse trace fossil assemblage | river-dominated distal delta front |
| | F3 | Interlaminated & interbedded siltstone and sandstone with very diverse trace fossil assemblage | wave-influenced distal delta front |
| | F4 | Hummocky to swaley cross-stratified sandstone | storm-dominated proximal delta front |
| | F5 | Blocky to fining upward trough cross-stratified sandstone | distributary channel |
| | F6 | Interlaminated & interbedded mudstone, siltstone and sandstone | interdistributary bay |
| | F7 | Coal seams and large coal lenses | swamp, marsh |
| | F8 | Blocky to coarsening upward sandstone with abundant *Ophiomorpha* | proximal delta front |
| FA2- Transgressive deposits | F11 | Sandstone with thin carbonaceous debris laminae and thin coal beds | washover deposits |
| | F12 | Striped mudstone with rare sand beds and laminae | brackish bay deposits |
| | F13 | Thin, sharp-based sandstone with abundant bioturbation | remnant of transgressive barrier |
| | F6 | Interlaminated & interbedded mudstone, siltstone and sandstone | lagoon |
| FA3- Prograding shoreface deposits | F4 | Hummocky to swaley cross-stratified sandstone | storm-dominated lower to middle shoreface |
| | F8 | Blocky to coarsening upward sandstone with abundant *Ophiomorpha* | lower to middle shoreface |
| | F14 | Bioturbated sandstone with horizontal to low angle inclined bedding | upper shoreface to foreshore deposits |
| | F9 | Hard, brown sandstone with carbonaceous rip-up clasts and plant debris | subaerial natural levee |
| | F7 | Coal seams and large coal lenses | swamp, marsh |
| FA4- Protected Bay Deposits | F10 | Burrow mottled sandstone | intertidal sand flats |
| | F11 | Sandstone with thin carbonaceous debris laminae and thin coal beds | washover deposits |
| | F12 | Striped mudstone with rare sand beds and laminae | brackish bay deposits |
| | F7 | Coal seams and large coal lenses | swamp, marsh |
| | F6 | Interlaminated & interbedded mudstone, siltstone and sandstone | lagoon |

Figure 2.18. Summary of facies and facies associations present in the transitional zone between the Bearpaw Formation and the Horseshoe Canyon Formation.

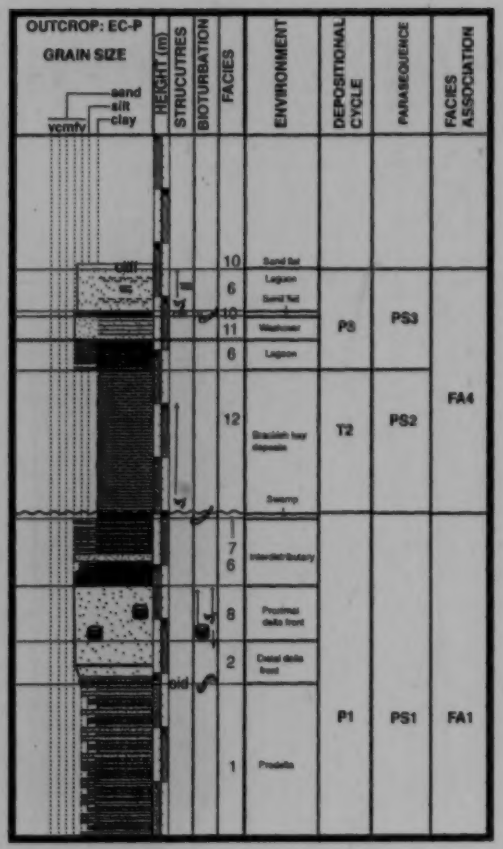
Figure 2.19 Logs showing interpreted relationships between the facies, facies associations, parasequences and depositional cycles present in the outcrops and in the subsurface.

A. Litholog of measured outcrop section EC-P (see fig. 1.1D for location). Note the presence of FA4 which is most prevalent in the northwest.

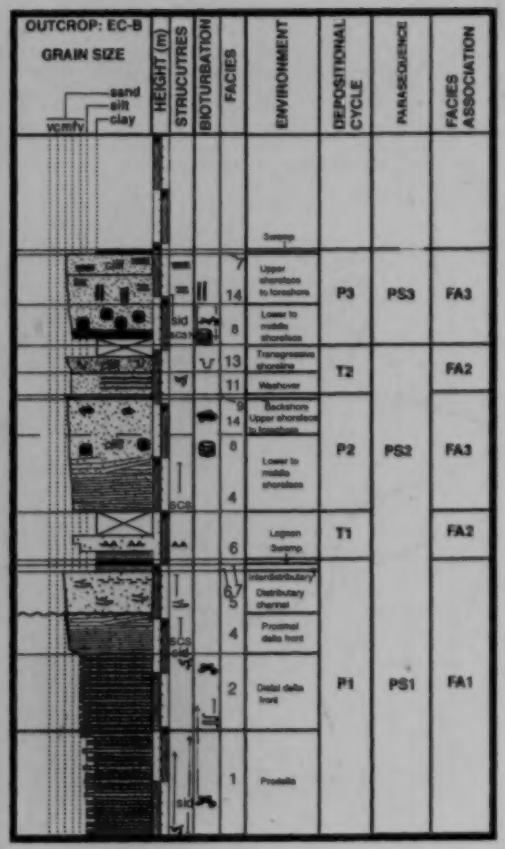
B. Litholog of measured outcrop section EC-B (see fig. 1.1D for location). Note that FA3 is present at two different stratigraphic horizons, which is common in the southeast.

C. Geophysical well log at 02/16-16-27-18W4 (see fig. 1.1C for location). Note the repetitive coarsening upward cycles represented by FA1 and FA3.

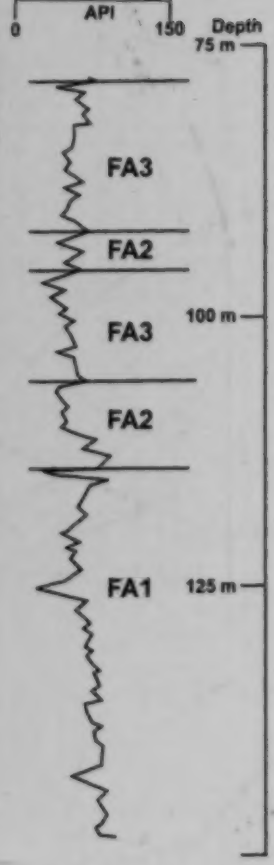
A.




B.




C. 02/16-16-27-18W4



through swamp and marsh environments, and facies maps indicate that the facies succession has a lobate geometry (Fig. 1.4C). FA1 is observed throughout the study area, in outcrops, drill cores, and geophysical well logs. FA1 is the lowermost facies association observed in the study area.

Two facies successions are seen in FA1. The most common facies succession seen in FA1 is F1-F7, with F1 being the basal facies in the facies association, and F7 being the top facies in the facies association. The second facies succession seen in FA1 is F1-F2-F8-F6-F7, with F1 being the basal facies, and F7 being the uppermost facies. The first facies succession occurs where distributary channels scour into the hummocky to swaley cross-stratified delta front. The second facies succession occurs where no distributary channels are present, and where the delta front does not experience intense wave reworking.

Facies association 2 (FA2) consists of F6 (lagoonal deposits), F11 (washover deposits), F12 (brackish bay deposits) and F13 (remnant transgressive barrier deposits), and is interpreted to represent a transgressive barrier system. The facies successions observed in FA2 are variable, and not all of the facies are present in every location. This is likely due to the high amounts of wave reworking that FA2 experienced. FA2 is observed at two different stratigraphic horizons throughout the stratigraphic interval in the study area.

Facies association 3 (FA3) consists of F4, F7, F8, F9 and F14 and is interpreted to represent a prograding shoreface complex, and most likely a barrier island or barrier spit complex. The facies successions observed in FA3 are somewhat variable, and not all of the facies are present in every location. However, a complete facies succession from lower shoreface to foreshore deposits is always observed. FA3 is observed at two different stratigraphic horizons throughout the stratigraphic interval studied in the study area.

Facies association 4 (FA4) consists of F6, F7, F10, F11 and F12 and is interpreted to represent protected bay deposits. The facies successions observed in FA4 are variable, and not all of the facies are present in every location. However, the facies association is always present on the paleolandward side of the interpreted barrier island/barrier spit facies. FA4 is observed at two different stratigraphic horizons throughout the stratigraphic interval studied in the study area. F4 is typically present on the paleo-landward side (northwest) of FA3.

The stratigraphy and paleogeography of the facies and facies associations is discussed in Chapter III, as well as some of the controversies regarding interpretations of the rock units in the study area.

# CHAPTER III

# DISCUSSION OF STRATIGRAPHY AND PALEOGEOGRAPHY

## Introduction

Deltaic deposits can be observed anywhere streams or rivers enter receiving basins, such as lakes, estuaries, bays, inland seas, or oceans. For delta accumulation to occur, substantial quantities of sediment must be supplied by the river. This sediment is then shaped and redistributed by the numerous processes mentioned previously. Initially, the term "delta" described triangular-shaped alluvial plain deposits such as are seen at the mouth of the Nile River (Coleman and Prior, 1982), however, other delta morphologies are also common.

Deltas are commonly classified as wave-dominated, river-dominated, tidally-dominated, or a combination, depending on the relative importance of each of these processes in the deposition of the delta (Galloway and Hobday, 1996) (Fig. 3.1). This classification is often further modified to include grain size (Orton and Reading, 1993). These different types of deltas exhibit different morphologies.

Although deltas are common in both the ancient and modern records, their popularity in published literature seems to have decreased alongside the growing popularity of sequence stratigraphy. This may be because deltaic systems are affected by many autocyclic processes such as delta lobe switching (Emery and Myers, 1996). This work places the deltaic facies into a stratigraphic framework based on facies stacking patterns and interpreted flooding surfaces.

The deposits observed in the outcrops near East Coulee are interpreted to belong to a large, multi-lobe deltaic complex. Cross-sections and facies maps (Figs. 1.4, 3.2, 3.3 and 3.4) of the rocks were constructed utilizing a combination of outcrop, drill core and geophysical well log data. The ichnologic and sedimentologic

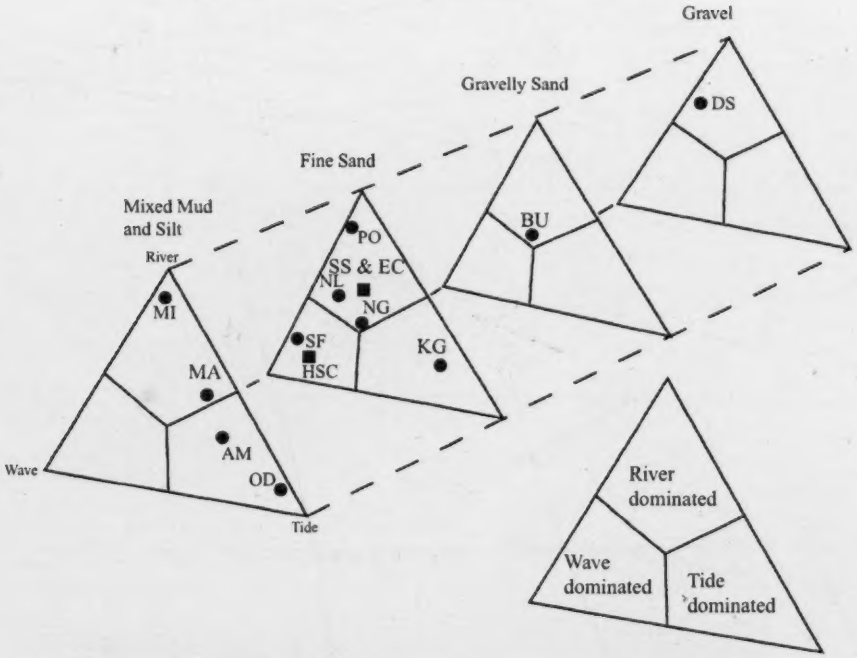



Figure 3.1. Differentiating between some deltas based on the relative amount of wave-, river-, and tide-dominance, and also the prevailing grain size within the delta. The lettered deltas are: MI-Mississippi delta (U.S.A.), AM-Amazon delta (South America), OD-Ord delta (Australia), SF-Sao Francisco delta (Brazil), NG-Niger delta (West Coast of Africa), PO-Po delta (Europe), DS-Dead sea delta, BU-Burdecan delta (Australia), KG-Klang delta (Malaysia), MA-Mahakam delta (Borneo), NL-Nile delta (Egypt). SS and EC refers to the two lowermost delta lobes discussed in this thesis, and HSC refers to the other delta lobes discussed in this thesis. Figure is modified after Orton and Reading (1993).

data observed in outcrops and drill cores provided necessary information to help reconstruct the paleogeography at the time of deposition (Fig. 3.6), and to interpret the stratigraphic architecture of the zone. An outcrop to subsurface correlation study such as this one can be extremely useful for providing a more complete picture of the stratigraphic evolution of the succession.

The deltaic deposition described here is interpreted to have occurred during highstand conditions, although sediment supply is considered to be the primary control on deposition (as opposed to sea level change). In general, highstand conditions include a decelerating rate of relative sea level rise, that results in aggradational and progradational sediment stacking patterns (Emery and Myers, 1996). Both progradational and aggradational sediment stacking patterns are interpreted to be present in the study area. Upward-coarsening, upward shoaling facies successions that are separated by thinner, upwards-deepening facies successions are recognized in the strata. These facies successions are referred to as parasequences (Emery and Myers, 1996) and occur within the highstand systems tract. Individual delta lobes are considered to represent single parasequences (Emery and Myers, 1996). There are two complete parasequences, and one partial parasequence recognized in the outcrops in the study area.

**Stratigraphic Datums**

Separating and correlating the Bearpaw and Horseshoe Canyon Formations is complicated by poor suitability of any horizon for use as a stratigraphic datum. Elliot (1960) astutely summed the situation up when he commented that the interest in the Edmonton Group may have dwindled in accordance with the lack of regionally extensive stratigraphic markers that could be used as suitable datums. "The time involved in correlating just doesn't seem to be worth the while," (Elliot, 1960).

Figure 3.2. Stratigraphic dip cross-section of the "EC" Delta Lobe (P1-progradational cycle) from northwest to southeast. Note the variable thickness of the distributary channel incisions, and that the distributary channels appear to have eroded the delta front somewhat. Also note that the geophysical well logs are all gamma ray curves, and that the horizontal distance on the cross-section is not to scale.

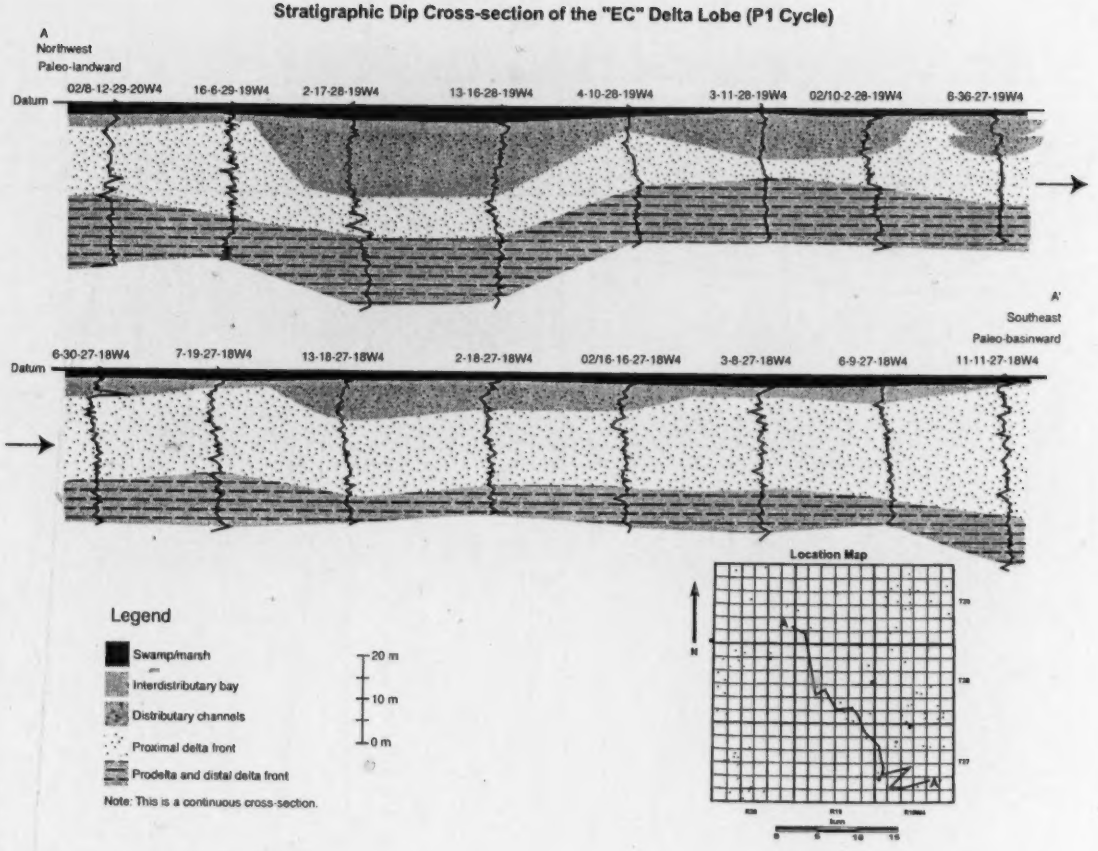

Stratigraphic Dip Cross-section of the "EC" Delta Lobe (P1 Cycle)
A
Northwest
Paleo-landward
Datum
02/8-12-29-20W4
16-6-29-19W4
2-17-28-19W4
13-16-28-19W4
4-10-28-19W4
3-11-28-19W4
02/10-2-28-19W4
6-36-27-19W4
A'
Southeast
Paleo-basinward
Datum
6-30-27-18W4
7-19-27-18W4
13-18-27-18W4
2-18-27-18W4
02/16-16-27-18W4
3-8-27-18W4
6-9-27-18W4
11-11-27-18W4
Location Map
N
A
A'
Legend
Swamp/marsh
Interdistributary bay
Distributary channels
Proximal delta front
Prodelta and distal delta front
20 m
10 m
0 m
Note: This is a continuous cross-section.

Figure 3.3. Stratigraphic strike cross-section of the "EC" delta lobe (P1-progradational cycle). Once again, note the variable thickness of the distributary channel incisions, and that the distributary channels appear to have eroded the delta front somewhat. Also note that the geophysical well logs are all gamma ray curves, and that the horizontal distance on the cross-section is not to scale.

## Stratigraphic Strike Cross-section of the "EC" Delta Lobe (P1 Cycle)

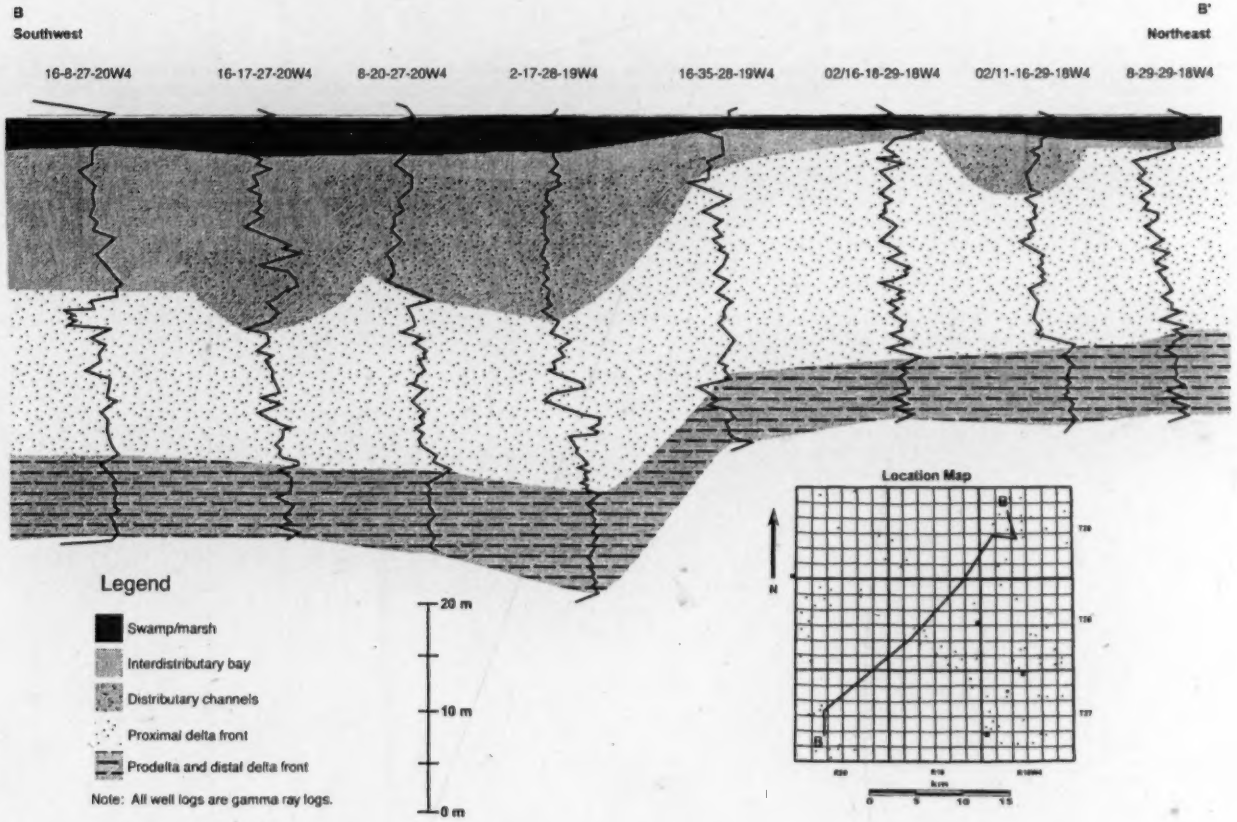


Figure 3.4. Outcrop cross-section near East Coulee, Alberta. This cross-section approximates the depositional dip of the strata. The cross-section shows the facies/ facies associations present in most of the measured sections studied for this thesis. The location of the cross-section and horizontal distances between outcrops can be seen in Figure 1.1D.

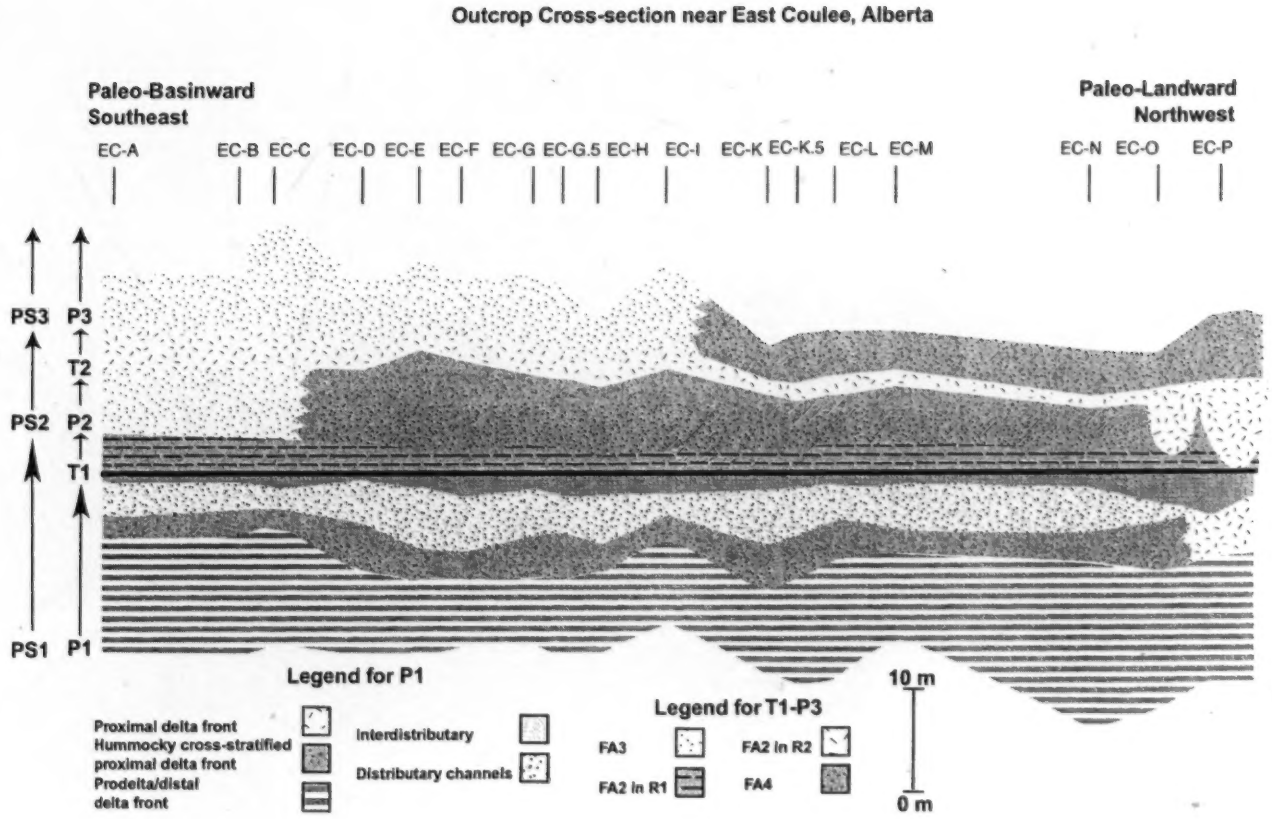

Outcrop Cross-section near East Coulee, Alberta
Paleo-Basinward
Southeast
Paleo-Landward
Northwest
EC-A
EC-B
EC-C
EC-D
EC-E
EC-F
EC-G
EC-G.5
EC-H
EC-I
EC-K
EC-K.5
EC-L
EC-M
EC-N
EC-O
EC-P
PS3
P3
T2
PS2
P2
T1
PS1
P1
Legend for P1
Proximal delta front
Hummocky cross-stratified
proximal delta front
Prodelta/distal
delta front
Interdistributary
Distributary channels
Legend for T1-P3
FA3
FA2 in R1
FA2 in R2
FA4
10 m
0 m

Figure 3.5. Chronostratigraphic correlation of the facies present in outcrops. Locations of and horizontal distances between outcrops can be found in figure 1.1D. Location EC-P-S refers to the south side of outcrop EC-P, and EC-P-N refers to the north side of outcrop EC-P.

The P1-Progradational Cycle represents progradation of the EC delta lobe.

The T1-Transgressive Cycle represents deposition of a transgressive barrier system that developed in part due to subsidence of the EC delta lobe.

The P2-Progradational Cycle represents progradation of a barrier/barrier spit complex that is part of a wave-dominated delta lobe. Note that the barriers shelter marine and brackish bays, and that deposition of these facies is coeval with channel (tidal inlet?) scour.

The T2-Transgressive Cycle represents deposition of a transgressive barrier system that likely developed in part due to subsidence of the P2 wave-dominated delta lobe. Note that the channel scours are filled upon transgression.

The P3-Progradational Cycle represents progradation of a barrier/barrier spit complex, similar to the P2.

## Chronostratigraphic Correlation of Outcrop Facies

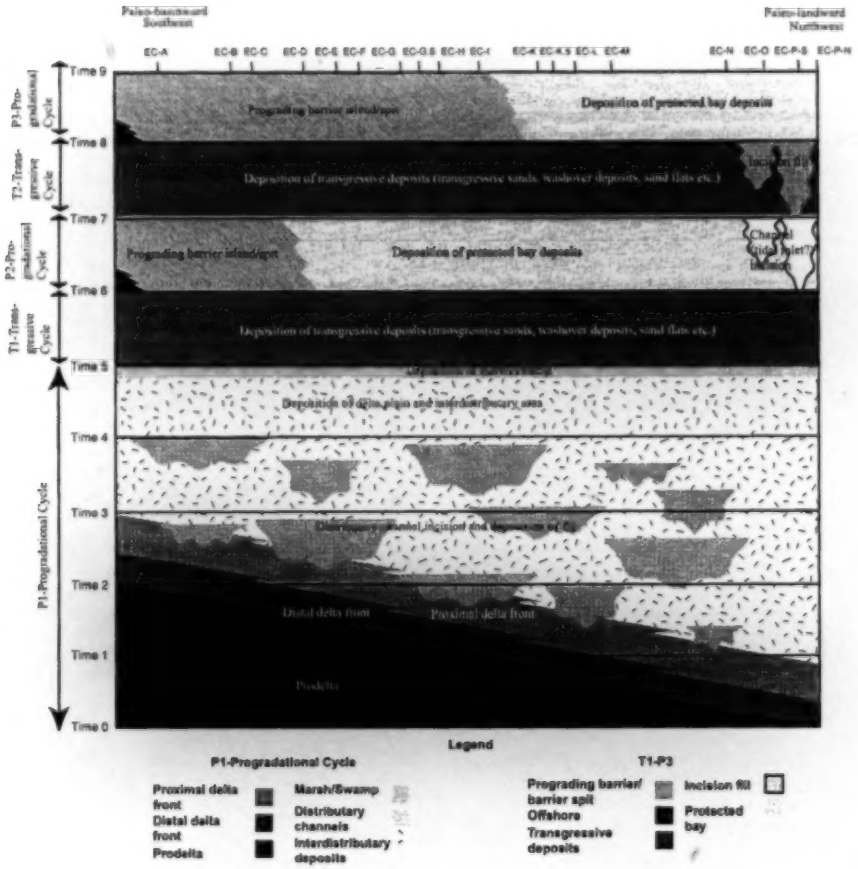


Figure 3.6. Interpreted paleogeography of the facies present in the study area.

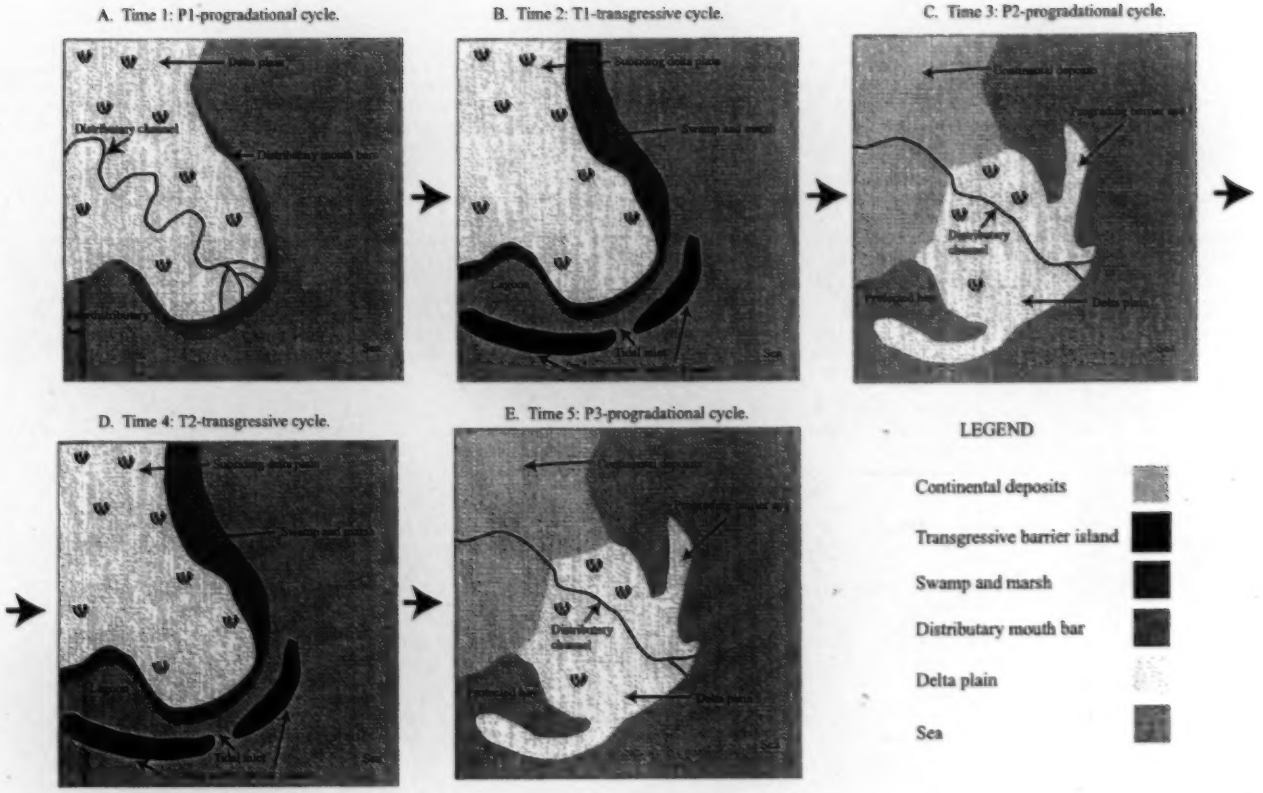
A. Time 1 represents the progradation of the EC delta lobe, or the P1-progradational cycle. Note the meandering nature of the distributary channels.

B. Time 2 represents the T1-transgressive cycle, or the transgression caused by subsidence of the EC delta lobe. Note that a transgressive barrier system developed, and that the channel system has moved.

C. Time 3 represents the P2-progradational cycle, or the progradation of wave-dominated delta lobe.

D. Time 4 represents the T2-transgressive cycle, or the transgression caused by the subsidence of the P2 delta lobe. Note that the channel system has moved.

E. Time 5 represents the P3-progradational cycle, or the progradation of another wave-dominated delta lobe.


A. Time 1: P1-progradational cycle.
B. Time 2: T1-transgressive cycle.
C. Time 3: P2-progradational cycle.
D. Time 4: T2-transgressive cycle.
E. Time 5: P3-progradational cycle.
LEGEND
Continental deposits
Transgressive barrier island
Swamp and marsh
Distributary mouth bar
Delta plain
Sea

The Knee Hills Tuff Zone, a regionally extensive volcanic ash that forms part of the Battle Formation (Elliot, 1960), makes an excellent regional datum. However, this volcanic ash is too shallow (i.e. it is too high stratigraphically) to be effective for local studies of the lower Horseshoe Canyon or the Bearpaw Formations.

The most effective datums found for local study of the Horseshoe Canyon Formation are coal seams and marine flooding surfaces. Using these surfaces is problematic, however, as the coal seams are often not regionally extensive and the flooding surfaces can be highly interpretive.

Coal 0 is used as a datum for this study (Figs. 3.2-3.4). Coal 0 is not a perfect datum, as it is not present in all locations. The stratigraphic horizon occupied by Coal 0 is sometimes occupied by a coaly shale or shale unit. However, there are no good stratigraphic surfaces present in all locations. Coal 0 is the surface most commonly present, it is less interpretive than the other surfaces that were considered.

A number of gamma ray log markers present below the base of the rocks studied in outcrop were considered for use as stratigraphic datums. These particular gamma ray log markers may represent flooding surfaces. However, these markers are not used for this study, as the author did not observe them in outcrops or drill cores, and as such, could not identify their natures. In addition, none of these markers could be identified in all locations.

**Discussion of Stratigraphy and Paleogeography**

The following discussion of the stratigraphy and paleogeography of the transition zone between the Bearpaw Formation and lower Horseshoe Canyon Formation is subdivided into five depositional units, which represent five chronostratigraphic successions. The stratigraphic interval is divided into the five chronostratigraphic successions depending on whether the shoreline is interpreted to be prograding or

not throughout the particular interval. As such, they are referred to as the P1 (progradational cycle), T1 (transgression cycle), P2, T2 and P3. The five chronostratigraphic units are not intended to represent any particular duration of time. These units make up two complete parasequences (PS1 and PS2) and one partial parasequence (PS3) (Fig. 3.4).

P1-Progradational Cycle

The P1 is the lowermost sediment package observed in outcrop. The P1 is comprised of all of the facies that make up FA1 (deltaic deposits), and represents a single delta lobe in a conformable deltaic succession. The P1 represents the first progradational cycle, or first basinward translation of the shoreline observed in the outcrops studied. The term progradation does not insinuate a drop in absolute sea level.

The P1 unit correlates to Shepheard and Hills' (1970) Units BP and E1, Rahmani's (1988) Unit 1, Saunders (1989) R1 regressive cycle, and Ainsworth's (1992, 1994) allomembers A and B.

The P1 is interpreted to represent the progradational EC delta lobe that is mapped in Fig. 1.4C, and shown in cross-section in Figs. 3.2-3.4. The timing of deposition of the P1 relative to the other rocks described in this thesis can be seen in Fig. 3.5. The SS delta lobe (Fig. 1.4B) prograded into the basin first. Lobe building in deltas results in a reduction of depositional gradient, resulting in channel avulsion (Coleman, 1976). Abandonment of the SS lobe was likely the result of this inherently deltaic process. The feeder channel eventually returned to the study area, to the approximate location indicated by Fig. 1.4C, and began supplying sediment to the coast. This allowed for the deposition of the EC lobe.

As noted in the facies interpretations, the EC lobe is considered a predomi-

nantly river-dominated delta, that experienced increased wave and storm influence over time. The P1 cycle represents a constructive phase of delta formation as described by Penland *et al.*, (1988). As discussed by Van Wagoner et al. (1990), deposition of the coastal plain sediments was coeval with progradation of the shoreline. This is reflected in Figure 3.5.

The P1 is considered to represent the upward-coarsening, upward shoaling portion of a single parasequence referred to here as Parasequence 1 (PS1). The P1 is bounded at the base by a major flooding surface, which marks the top of the transgressive unit at the top of the SS delta lobe. The top of the P1 is marked by a flooding surface that denotes the base of the T1. This contact likely experienced no appreciable erosion.

This interpretation of a conformable deltaic succession differs from some previous interpretations in two main ways. The first is with regards to Facies 4, the proximal delta front.

Ainsworth (1992, 1994) indicated that the base of this facies is sharp towards the northwest (paleo-landward), and gradational towards the southeast (paleo-basinward). Ainsworth (1992, 1994) suggested that the sharp-based nature of the shoreface (or delta front) in the northwest may indicate a forced regression (Plint, 1988). Forced regressive shorefaces develop when the cause of progradation is a drop in sea level. The sea level fall results in decreased accommodation space, and scouring of the shelf by waves in advance of the rapidly prograding shoreface (which creates an erosional surface). As such, a thin, "sharp-based" shoreface sand lies directly on top of offshore sediments.

The author observes both gradational and sharp bases to Facies 4 throughout the study area, however does not interpret the sharp-based sand body to represent a forced regression. In most of the outcrops, the sharply based sand body is interpreted

to represent storm deposition indicated by the presence of hummocky to swaley cross-stratification. Hummocky and swaley cross-stratified beds are commonly sharply based, as they represent rapid emplacement of proximal sediments onto the offshore sediments by storms. These storm beds do not settle slowly out of suspension. Differences in sediment reworking throughout space and time, differences in relative densities of water bodies, and grain size variations may also play a role in the nature of sediment deposition and mixing (see Orton and Reading, 1993 and Reading and Collinson, 1996). For example, homopycnal flow (i.e. the river and basin waters are of equal density) tends to generate intense 3-dimensional mixing near the river mouth (Reading and Collinson, 1996). As such, gradational contacts would be expected. However, hypo- or hyper-pycnal flows would not promote as high a degree of sediment mixing.

The second way in which the interpretation of a conformable, deltaic succession differs from some previous interpretations is with regards to the origin of, and type of channel that is represented by Facies 5. This has been the subject of much debate. Shepheard and Hills (1970) studied outcrops directly north of, and northwest of the outcrops studied for this research. They interpret F5 to represent a distributary channel facies related to the underlying deltaic complex. Lavigne (1999) and studied many of these same outcrops, and concurs with their interpretations.

Rahmani (1988) examined these same outcrops, as well as a number of drill cores and some geophysical well logs. Many of Rahmani's (1988) outcrop observations are similar to those made by Shepheard and Hills (1970) and Lavigne (1999). Rahmani's (1988) interpretations, however, are somewhat different.

Rahmani (1988) interpreted the scour at the base of the channel to have been enhanced by a drop in relative sea level. Rahmani (1988) stated that this was then followed by submergence and transgression, and formation of tidal estuarine

conditions in the deepened distributary channel. As such, Rahmani (1988) interpreted Facies 5 to represent an estuarine, incised valley fill, with an unconformity at the base. Rahmani (1988) likened the deposition of F5 to that of a tripartite estuary such as the Gironde estuary in France (see Allen, 1991). Rahmani (1988) showed a map of this estuary in the subsurface (see Fig. 1.7), and indicated that the tripartite facies distribution can be observed in geophysical well logs. Ainsworth (1992, 1994) agreed with most of Rahmani's (1988) assessments, and placed a sequence boundary at the base of Facies 5. Eberth (1996) and Eberth in Eberth and Lavigne (2002) also agreed with this viewpoint.

So, the question remains: does the base of Facies 5 represent a sequence boundary? A number of characteristics complicate the correct interpretation of this facies. Most of the salient points to this debate were discussed by Lavigne (1999). A quick summary of some of the issues is provided here.

Firstly, there are no trace fossils present in F5. In general, brackish settings (whether deltaic or estuarine) can often be identified based on ichnological criteria (Pemberton and Wightman, 1992). This apparent lack of bioturbation could indicate continental conditions, extreme salinity changes, high sedimentation rates (masking the burrows) or it could indicate something different altogether. Double mud drapes are also present, and may indicate a marine environment. However, tidal currents can travel up-stream long distances, especially in low gradient settings such as those present on this coastline during the Upper Cretaceous. Distributary channels in conformable deltaic settings may experience some estuarine conditions. As such, neither the ichnological characteristics nor the presence of tidal indicators supports one interpretation more than the other. That is to say, neither characteristic indicates whether the P1 represents a conformable succession or not.

A second problem is that the lateral margins of the channel(s) cannot be

directly identified in outcrops or drill cores. Because the lateral margins of the channel(s) cannot be identified directly, it is difficult to know exactly what sediments it/ they erode into, or its/their exact configuration.

Thirdly, the significance of the width of the channel(s) is controversial. As can be seen on Figure 2.9C, the thickest portions of the channel appear to be over six km wide. This large width may support an incised valley interpretation. However, it is equally possible that this thicker portion of the facies represents a number of different distributary channels flowing through the same area. This is not uncommon in modern deltas. The Mississippi Delta, for example, has an average meander-belt width of approximately 16 km, and the Niger River Delta has an average meander-belt width of approximately 10 km (Coleman and Prior, 1982). In addition, there is no consensus as to whether F5 occupies only one stratigraphic horizon, or multiple stratigraphic horizons. If the incision only occurs at one stratigraphic horizon, it may indicate lowstand conditions at the time. However, if the incisions occupy more than one stratigraphic horizon, it may indicate the presence of distributary channels. Ainsworth (1994) indicated that the base of F5 is scalloped and irregular along Willow Creek, northwest of the outcrops studied for this thesis, which suggests that the base of F5 may be comprised of a series of smaller incisions.

The depth of erosion of the channel(s) has also been presented as evidence for the presence of an incised valley system. For example, Ainsworth (1994) indicated that the channel(s) incise(s) into offshore marine mudstones, and cites this as possible evidence for base level change. However, these "offshore marine mudstones" are interpreted here to represent prodelta muds, and distributary channels often incise into the prodelta (Coleman and Prior, 1982). The maximum incision depth noted by the author is approximately 13 m (although Rahmani (1988) indicated an incision depth up to 20 m). However, an incision depth of approximately 7 to 8 m is much more

common. A number of modern deltas experience distributary channel incision depths that are equal to or greater than those seen in the Horseshoe Canyon Formation, such as in the Niger River Delta (10-15 m) (Coleman and Prior, 1982).

In the author's opinion, no conclusive evidence for either side of the debate has been presented thus far. However, the author considers there to be more evidence supporting the conformable deltaic succession interpretation for two main reasons. Firstly, Rahmani (1988) and Ainsworth (1994) emphasized that a rooted horizon observed at EC-7 (Rahmani, 1988) or RDV-8 (Ainsworth, 1994) provided evidence for subaerial exposure during the time of relative sea level fall. The author also observed this rooted horizon at EC-7/RDV-8, but did not observe any roots to be present at the correlative stratigraphic horizon in EC-P on the south side of the river (Fig. 3.4). As such, this rooted surface does not appear to be a widespread occurrence. In addition, proto-seagrass or seagrass is believed to have been well developed and widespread by the end of the Cretaceous (Larkum and den Hartog, 1989). As seagrass grows and develops under subaqueous conditions, the presence of roots in Late Cretaceous or younger sediments should not be used as definitive evidence for subaerial exposure. As such, the localized rooted surface at EC-7/RDV-8 most likely does not indicate the presence of an interfluve.

Secondly, facies mapping (see Fig. 1.4) and outcrop study indicates the presence of a multi-lobe delta complex that existed for some time. There is no conclusive evidence indicating that rapid changes in base level were responsible for the deposition of the facies. It appears that sediment supply, and the relative amount of river vs. wave influence primarily shaped the nature of the deltaic system. As such, the author believes there is more evidence supporting a deltaic distributary channel interpretation for F5. FA1, and P1 are interpreted to represent a conformable, deltaic succession. A schematic diagram of the paleogeography of the P1 can be seen in Fig. 3.6A.

T1-Transgressive Cycle

The Horseshoe Canyon T1 represents the first transgressive cycle, or first landward translation of the shoreline observed in the rocks studied. The T1 overlies the P1 and underlies the P2. The T1 is comprised primarily of F6 (lagoonal deposits) and F11(washover deposits) which belong to FA2 (transgressive deposits) (Fig. 2.18). These rocks are interpreted to represent washover and lagoonal facies that were deposited as part of a transgressing barrier island system (Figs. 3.4, 3.5 and 3.6B).

The T1 appears to correlate to the lower portion of Shepheard and Hills' (1970) Unit E2, the lower portion of Rahmani's (1988) Unit 2, Saunders' (1989) transgressive cycle T2 and the lower portion of Ainsworth's (1992, 1994) allomember C. The outcrops studied by those workers were not studied in detail by the author.

The T1 is interpreted to represent a natural progression of the EC delta from the underlying constructive phase (P1) to a destructive phase caused by delta lobe abandonment and subsidence (Penland *et al.*, 1988). After the EC lobe built out into the basin, the feeder channel system lost its gradient advantage, and the lobe was abandoned, much like is seen with the SS lobe. As such, the EC lobe was subjected to subsidence and wave reworking. Transgression ensued, and a transgressive barrier complex was established. As is also seen in the St. Bernard lobe in the Mississippi River delta, sands and silts concentrated by wave processes likely allowed for formation of the barrier(s). These processes are further discussed by Coleman (1976). The coastal plain deposits (lagoonal deposits) in the T1 are coeval with the transgression, as was discussed by Devine (1991).

The T1 is interpreted to represent the upwards-deepening portion of parasequence 1 (PS1). The upward deepening component of a parasequence is often represented only by a surface marking the transition from shallower to deeper water (Emery and Myers, 1996). However, as is seen in the T1, a thin transgressive unit is

sometimes preserved. The top of the T1 is a major flooding surface.

P2-Progradational Cycle

The P2 represents the second progradational cycle, or second basinward translation of the shoreline observed. The P2 overlies the T1 and underlies the T2. The P2 is comprised of a combination of FA3 (prograding shoreface deposits) and FA4 (protected bay deposits). As such, these rocks are interpreted to represent a prograding barrier or barrier spit, with protected bay deposits on the landward side (Figs. 3.4, 3.5 and 3.6C). It is suggested here that this prograding barrier/ barrier spit complex reflects the formation of another delta lobe (constructive phase) that is predominantly wave-dominated (as opposed to river-dominated like the EC lobe). Increased wave influence is noted in the younger facies. In addition, some channel scours appear to have occurred during the P2 towards the northwest, as can be seen on Figure 3.4 and 3.5. These incisions may have been caused by tidal inlets.

The classification of the P2 as a delta lobe may be considered contentious by some authors as some of the sediment was likely not river derived. A similar situation occurs in the Sao Francisco "Delta". This "delta" is considered by some to be a wave-dominated delta (Coleman, 1976), but by others to be a beach-ridge strandplain system (Reading and Collinson, 1996). This is because the system is supplied with a considerable amount of sediment via longshore drift, as opposed to only from a river. Very few coastlines have only one sediment source, however, and deltaic and strandplain systems may be gradational with one another. Although the P2 has a pro-grading, wave-influenced barrier/barrier spit system on the basinward side, it is still considered part of a delta system. This is primarily because the overall depositional system appears to experience relatively consistent progradational-transgressive cycles that resemble the delta lobe-switching process. Unfortunately at present, not enough

subsurface data exists to map the aerial extent of any of the facies that overly the P1 cycle. Increased data in the future may confirm or contest these interpretations.

During flooding of the delta plain (the T1 transgression), a significant lagoonal system developed on the landward side of the transgressing barriers. However, at some point, sediment supply exceeded the rate of creation of accommodation space, and the P2 progradational barrier island/barrier spit system was able to form. This barrier system was likely composed of both river-sourced sediment, and longshore drift supplied sediment. However, many of the preserved deposits (sand flats, lagoons, brackish bays etc.) indicate that a significant protected area persisted behind the prograding barriers for some time. The formation of transgressive or stillstand barrier islands has been the topic of much research (ex. Dickenson *et al.*, 1972; Reinson, 1992 and Cooper, 1994). Regressive barrier islands have been less documented in literature, however. This is likely because, as sea level falls, the backbarrier portion of the prograding barrier system fills in with sediment and the regressive barrier island becomes a prograding strandplain (Roy, et al., 1994). It may seem odd that the barrier system described here should exist at the same time as a significant lagoonal system.

If the sediment supply is sufficient to source a prograding barrier system during a slowly rising sea level, however, a lagoonal system may persist without being filled in with sediment. This is thought to be the case in the P2.

A number of examples of this are observed in the modern record. One example is that of the Nayarit Coast, on the west coast of Mexico, as discussed by Davis and Clifton (1987). This coast is a prograding, predominantly wave-dominated coast that consists of an extensive system of barriers and lagoons.

A rapid transgression occurred from about 18 ka until 7 ka on this coast, resulting in the development of a transgressing barrier-lagoon-marsh system (although the transgressive barriers are not preserved). Around 4.75-3.6 ka the coastline started

to prograde. This progradation was not accompanied by a fall in sea level, but rather by a slowing of sea-level rise. The combination of reworking of older sediments and the addition of newer fluvial sediments led to the wave-dominated, progradational beach-ridge complex that exists alongside the lagoons today.

A second modern example of a prograding barrier spit system coexisting with an extensive protected bay is that of Willapa Bay, Washington, which was discussed by Clifton and Phillips (1980). Willapa Bay is a large estuary (or bay) on the south coast of Washington with extensive protected bay deposits that are separated from the Pacific Ocean by a large, prograding spit.

Transgression during the Holocene originally affected this highly embayed coast. The rate of sea level rise eventually slowed, however, and sediment supplied (at least in part) by the Columbia River accumulated. Localized wave-dominated conditions cause some barrier spits to begin to form across the embayments. The slow rise in sea level, however, still allows for the protected bay deposits to persist.

A third modern example was observed on the coast of eastern Ghana and Togo (Anthony and Blivi, 1999). This coast is part of a regional sand barrier complex that shelters lagoons in the Gulf of Guinea.

Sea level rise during the Holocene resulted in the deposition of transgressive barriers that sheltered marsh and lagoonal muds. At some point, sediment supplied from nearby cliffs, from reworking of the transgressive barrier sands, and from longshore drift from the nearby Volta Delta allowed for shoreface progradation. This appears to have happened during a slowing in sea level rise, or relative stillstand. The protected bay deposits persisted behind the prograding barriers, however, and still exist today.

An ancient example is described by Carter (1978) in the Upper Tertiary Cohansey Sand of southern New Jersey. A progradational barrier with a complete

suite of progradational barrier facies co-exists with barrier protected deposits and appears to be largely age-equivalent to them. Although Carter (1978) does not provide an in-depth discussion explaining the distribution of facies, it seems likely that the Cohansey Sand was deposited in much the same way as the preceding three examples.

The P2 is interpreted to represent the upward-coarsening, upward-shoaling portion of a parasequence, PS2. As such, there is a major flooding surface at its base.

The P2 appears to correlate to the upper portion of Shepheard and Hills' (1970) Unit E2, the upper portion of Rahmani's (1988) Unit 2, Saunders' (1989) R2 regressive cycle and the upper portion of Ainsworth's (1992, 1994) allomember C.

T2-Transgressive Cycle

The Horseshoe Canyon T2 represents the second transgressive cycle, or second landward translation of the shoreline observed. The T2 overlies the P2 and underlies the P3. The T2 is composed of all of the facies present in FA2 (transgressive deposits). As such, these rocks are interpreted to represent a transgressive barrier or barrier spit system, including transgressive shoreface sands, washover deposits, lagoonal sediments, and quiescent brackish bay deposits (Figs. 3.4, 3.5 and 3.6D). The T2 is interpreted to represent a destructive delta phase that followed the P2.

After progradation of the P2 cycle ended, the delta lobe subsided and a second transgressive event occurred (T2). Transgressive barrier islands developed, and are preserved as a thin, sharp-based transgressive shoreface and washover deposits. On the landward side of the barrier, lagoonal sediments developed, and quiescent brackish bay sediments were deposited in channel scours developed during formation of the P2. The P2 scours are believed to have been filled during transgression due to their

muddy natures (interpreted to have been deposited by suspension deposition) than the surrounding sediments, and due to the presence of marine and brackish trace fossil assemblages present in the fills.

The T2 is interpreted to represent the upward-deepening facies succession associated with parasequence 2 (PS2). The top of the T2 is marked by a major flooding surface. The T2 appears to correlate to Shepheard and Hills' (1970) Unit E3, Rahmani's (1988) Unit 3, Saunders' (1989) T3 transgressive cycle and Ainsworth's (1992, 1994) allomember D and possibly allomember E.

P3-Progradational Cycle

The P3 represents the third progradational cycle, or third basinward translation of the shoreline observed. The P3 overlies the T2, and is the uppermost depositional cycle described here. The P3 is composed of a combination of FA3 (prograding shoreface deposits) and FA4 (protected bay deposits). As such, these rocks are interpreted to represent a prograding barrier or barrier spit system, with protected bay deposits on the landward side (Figs. 3.4, 3.5 and 3.6E). The P3 is interpreted to represent another wave-dominated delta lobe.

The P3 cycle is interpreted to have been deposited in a similar manner to the P2 cycle. A change in sediment supply and sediment distribution allowed for the development of a prograding barrier or barrier spit to develop, and co-exist with protected bay deposits that are primarily transgressive in nature.

The P3 is interpreted to represent the upwards-coarsening, upward-shoaling portion of a parasequence (PS3). As such, the base is interpreted to represent a flooding surface.

The P3 appears to correlate to Shepheard and Hills' Unit E4 and part of Unit E5, Rahmani's (1988) Unit 4, Saunders' (1989) R3 Appaloosa cycle, Ainsworth's

(1992, 1994) allomember F and possibly Ainsworth's (1992, 1994) allomember E.

**Summary**

Overall, the depositional units discussed in this chapter represent a series of deltaic lobes that change from predominantly river-dominated to more wave-influenced through time. These rocks were deposited during an overall retreat of the Bearpaw Sea from the study area. It is noted that PS1 is mostly progradational in nature, which is consistent with the retreating sea level. PS2 and PS3 appear to have experienced conditions of slowly rising sea level, however. This is believed to be due to the nature of the depositional system (i.e. lobe abandonment and subsidence), however, rather than rapidly fluctuating base level. It is most likely that the rate of sediment supply was very close to the rate of sea level change at these times. PS2 and PS3 likely represent largely aggradational stacking patterns during the highstand conditions that permitted deposition of this delta system as a whole.

# CHAPTER IV

# CONCLUSIONS

1) In Townships 27-29, Ranges 18-20 west of the 4th Meridian, the facies present in the transition zone between the Bearpaw Formation and the Horseshoe Canyon Formation represent deltaic and associated environments. These facies can be grouped into four facies associations that make up five depositional cycles. These five depositional cycles make up one incomplete parasequence and two complete parasequences that were deposited due to delta lobe switching.

2) The delta lobes present in the study area can be classified as either river-dominated or wave-dominated. The different classification is based on the different delta lobe morphologies, and the differences in the trace fossil assemblages. The trace fossil assemblages in the river-dominated delta lobes indicate stressful living conditions, and the ichnofossils are less abundant, and less diverse than in the wave-dominated facies successions.

3) The P1-progradational cycle represents a conformable deltaic succession. There is no evidence to support the existence of a sequence boundary at the base of the delta distributary channels (F5).

4) The sharp base of the delta front in the P1-progradational cycle does not indicate a forced regression. The sharp base is likely due to storm activity, and variable environmental conditions within the delta.

5) In the wave-dominated delta lobes, the prograding barrier islands/barrier spits are coeval with lagoons, and exist during slowly rising sea level.

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# APPENDIX I

## A Fecal Pellet-Burrow Trace Association: Evidence for a Modern Analogue for the Tracemaker of *Ophiomorpha borneensis?*

### Introduction

The trace fossil *Ophiomorpha* is one of the more commonly recognized trace fossils in literature (ex. Bromley and Frey, 1974, Howard and Frey, 1984 and Frey and Howard, 1990). These knobby-walled burrow traces are easy to identify both in outcrops and drill cores and are a common constituent of facies interpreted to represent beach and neritic sands (Frey *et al.*, 1978). As is common in the field of ichnology, however, the identity of the tracemaker is uncertain.

A number of modern organisms have been suggested to be possible modern analogues for the tracemaker responsible for the ichnofossil. The most commonly suggested modern analogue for the tracemaker is the mud-dwelling shrimp *Callianassa* sp. Many workers have suggested evidence for this association including Hoyt and Weimer (1963), Weimer and Hoyt (1964), Howard and Dorjes (1972) and Frey et al. (1978). Other possible modern analogues include *Upogebia* sp. (Frey *et al.*, 1978) and *Axius* sp. (Pemberton *et al.*, 1976). These three genera are suggested to be possible modern analogues because they all construct knobby-walled burrows that look similar to *Ophiomorpha*. At present, the only direct evidence that may support these claimed associations are isolated cases of thalassinidean remains (Rasmussen, 1971; Kriz and Cech, 1974 and Stilwell *et al.*, 1997) and fecal pellets (Brown, 1939 and Kennedy *et al.*, 1969) preserved associated with some burrow traces.

A vast quantity of literature exists that discusses modern or ancient fecal pellets, but little effort has been spent to determine the potential associations between the modern and ancient specimens. Paleontologists especially appear to be overlooking

the modern biological studies that may greatly aid their research, and consequently, some incorrect conclusions have been perpetuated (ex. Bronnimann *et al.*, 1972 and Senowbari-Daryan, 1979). The purpose of this study is to summarize the state of fossil fecal pellet research to date and discuss a rare occurrence of *Palaxius decemlunulatus* (fecal pellets) present within *Ophiomorpha borneensis* (burrow traces) in the Upper Cretaceous of Western Canada. In addition, weaknesses and mistakes in earlier research on ancient fecal pellets, and areas for future work are highlighted.

**Previous Work and Background Information**

*The burrow trace*

The ichnogenus *Ophiomorpha* was first described by Lundgren (1891) as simple to complex burrow traces with mammalated walls (Figs. 1B,C and D). Subsequently, a number of ichnospecies have been identified based on differences in the mammalations. These include *Ophiomorpha nodosa* (Lundgren, 1891), *Ophiomorpha annulata* (Frey and Pemberton, 1985), *Ophiomorpha irregulaire* (Frey at al., 1978) and *Ophiomorpha borneensis* (Keij, 1965). There is no consensus regarding the cause of the burrow wall variabilities (Frey *et al.*, 1978), however, the different ichnospecies can be easily differentiated from each other based on their unique configurations.

*Ophiomorpha* is commonly present in facies interpreted to represent nearshore and beach deposits, and as such, has some value as a facies indicator. The burrow traces can be quite variable, however, and the tracemaker(s) is/are still uncertain. A comprehensive review of the state of knowledge of *Ophiomorpha* can be found in Frey *et al.* (1978).

Figure 1: *Ophiomorpha* in outcrops and hand samples.

A. *Ophiomorpha borneensis* network in outcrop at EC-B (Chapter 1, fig. 1.1D). Most of the darker portion of the picture represents these burrow traces. The central sand mound contains abundant burrow traces, making it resistant to erosion. Ice axe is 78 cm long.

B. Close-up of *Ophiomorpha borneensis*. Scale bar is 15 cm long.

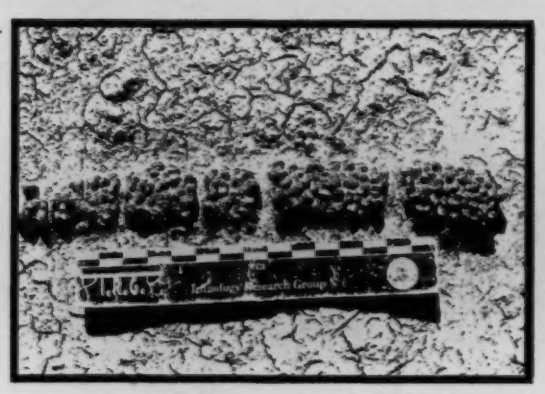
C. *Ophiomorpha* in hand sample. Note the spheroids that make up the burrow trace walls.

D. Cross-section view of burrow traces.

A.

Burrow traces

B.



C.

D.

*Fecal pellets*

Although they were not originally identified as such, fossil fecal pellets were first described by Joukowsky and Favre (1913), and were referred to as Orgānism B, a problematic fossil.

Early modern fecal pellet work was conducted by Moore (1931a, 1931b, 1932, 1939) and Moore and Kruse (1956). Specifically, Moore's (1932) discussion of modern fecal pellets forms the basis for many of the assumptions and conclusions discussed in ancient fecal pellet studies today. Moore (1932) showed that some fecal pellets contain distinctive internal canals that vary in shape, number and configuration between different genera and species. However, little variation is present among specimens of the same species. Moore (1932) noted that internal canals are present in very few types of fecal pellets, and hence, may prove significant for the classification of species possessing such distinctive characteristics.

Moore (1932) indicated that these canals are due to the presence of a system of processes within the stomachs of the organisms. These processes project inward, and point like fingers into the posterior end of the stomach. Semi-fluid food flows around the "fingers", and then passes into the intestine in a more solidified state, retaining the shape of the processes in the excrement. Powell (1974) explained this process clearly and in detail, using the guts of *Neotrypaea* (as *Callianassa*) *californiensis* and *Upogebia pugettensis* as examples (Fig. 2). This process is also discussed using the guts of *Porcellana platycheles, Galathea squamifera* and *Upogebia deltaura* by Ngoc-Ho (1984). Unfortunately, fossil researchers seem to be unaware of these modern works, as only Moore's (1931a, 1931b, 1932 and 1939) explanations are typically discussed.

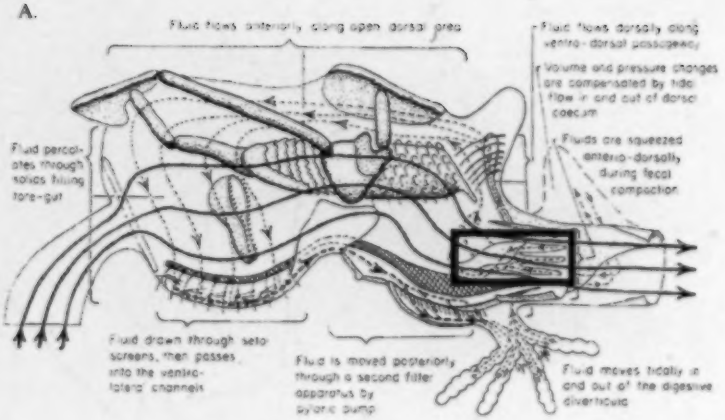
After studying Moore's (1931a, 1931b, 1932 and 1939) work, Parejas (1948) identified fossilized remains similar to Organism B (Joukowsky and Favre, 1913) as

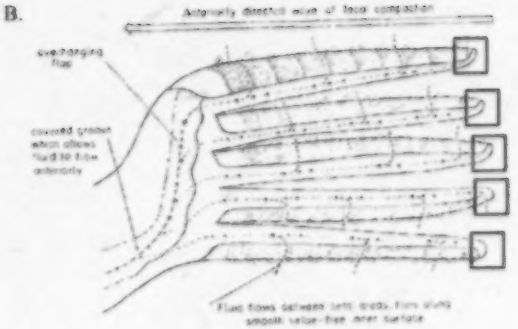
Figure 2: Diagram of internal structures of *Neotrypaea* (as *Callianassa*) *californiensis*. From Powell (1974).

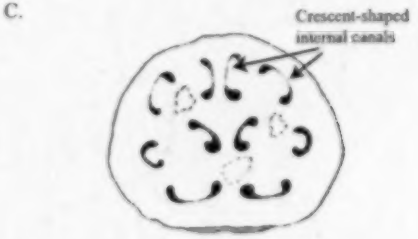
A. Representation of movements of solids (solid black arrow) and circulation of liquids in the foregut (dotted black arrows). Large dark box indicates the relative position of the pyloric fingerlets that are highlighted in B.

B. Diagram shows fluid flow along the pyloric fingerlets. Fluid passes from fecal column and flows anteriorly along pyloric fingerlets into pyloric stomach. The shape of the end of these fingerlets (highlighted by small black boxes) determines the shape of the internal canals in the fecal pellets in C.

C. Diagrammatic fecal pellet from *Neotrypaea californiensis*. Note that the end of the fingerlets in B are crescent shaped, and as such, the fecal pellets contain crescent-shaped internal canals.


A.
Fluid flows anteriorly along open dorsal area
Fluid flows dorsally along ventro-dorsal passageway
Volume and pressure changes are compensated by tidal flow in and out of dorsal caecum
Fluids are squeezed antero-dorsally during fecal compaction
Fluid percolates through setae filling fore-gut
Fluid drawn through seta screens, then passes into the ventro-lateral channels
Fluid is moved posteriorly through a second filter apparatus by pyloric pump
Fluid moves tidally in and out of the digestive diverticula


B.
Anteriorly directed wave of fecal compaction
overhanging flap
grooved groove which allows fluid to flow anteriorly
Fluid flows between setal ends, then along smooth setae-free inner surface


C.
Crescent-shaped internal canals

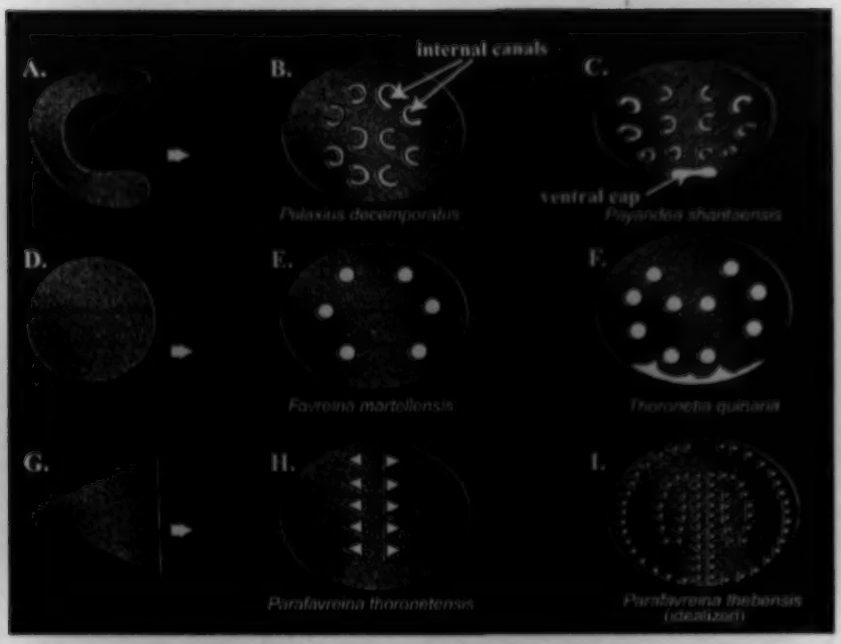



**Figure 3. Some types of fossilized fecal pellets.**

**A. The crescent shaped internal canal is present in both *Palaxius* isp. and *Payandea* isp.**

**B. Idealized *Palaxius decemporatus*. Note the presence of crescent shaped internal canals and the absence of a ventral cap of finer grained sediment that characterizes the ichnogenus.**

**C. Idealized *Payandea shantaensis*. Note the presence of the ventral cap of finer grained sediment at the base of the pellet that differentiates this ichnogenus from *Palaxius* isp.**

**D. The circular or ovoid shaped internal canal is present in both *Favreina* isp. and *Thoronetia* isp.**

**E. Idealized *Favreina martellensis*.**

**F. Idealized *Thoronetia quinaria*. Note presence of the ventral cap.**

**G. The triangular shaped internal canal characterizes *Parafavreina* isp.**

**H. *Parafavreina thoronetensis*.**

**G. *Parafavreina thebensis*.**

being fossilized fecal pellets of crustaceans. Parejas (1948) named the specimens *Coprolithus decem lunulatus*. Unfortunately, Parejas (1948) did not define the ichnogenus, nor designate a type ichnospecies, so the generic name *Coprolithus* was invalid under the International Rules of Zoological Nomenclature.

Bronnimann (1955) erected a new ichnogenus, *Favreina* isp., for the specimens previously referred to as Organism B (Joukowsky and Favre, 1913). The ichnogenus *Favreina* isp. contains all fossil fecal pellets that have rounded or ovoid internal canals (Fig. 3E). Bronnimann (1955) initiated the classification scheme for fossil fecal pellets in which ichnogenera are determined by the shape of their internal canals and the presence or absence of a "ventral cap" (a layer of finer sediment at the base) (Figs. 3C and F). The ichnospecies are determined by the number of internal canals in the pellets. Bronnimann and Norton (1960) introduced the ichnogenus name *Palaxius* isp. for all coprolites showing crescent or hook shaped canals in transverse section such as those described by Parejas (1948) (Fig. 3B). Bronnimann and Norton (1960) preserved Parejas' (1948) ichnospecies name (*decem lunulatus*) for coprolites with 10 crescent-shaped canals (Fig. 5). Numerous other ichnogenera have been designated since, including *Parafavreina* isp. (triangular shaped canals) (Figs. 3H and I), *Thoronetia* isp. (circular canals with ventral cap) (fig. 3F), and *Payandea* isp. (crescent shaped canals with ventral cap) (Fig. 3C).

Although Bronimann's (1955, 1960) classification system was debated by authors such as Elliot (1962), the naming scheme was utilized by many other workers (ex. Senowbari-Daryan and Grotsch, 1992, and Blau et al., 1995) and has been adopted into the Treatise on Invertebrate Paleontology (Hantzschel, 1975). (Hantzschel (1975) provided a complete summary of the classification of fossilized fecal pellets.

The earliest known possible fossil fecal pellet-burrow trace association is that

of Brown (1939), although he identified the burrow trace as *Halymenites major*, believing it to be a plant. This burrow trace is in fact *Ophiomorpha*, and is noted to contain "phosphatic pellets" that may be fossilized fecal pellets. Another fossil fecal pellet-burrow trace association is discussed by Kennedy *et al.* (1969) in the Great Oolite Series at Kirtlington, Oxfordshire. The burrow trace system is comprised of *Thalassinoides* that contain fecal pellets identified to be *Favreina decemlunulatus* inside the burrow traces. These fecal pellets would now be referred to as *Palaxius decemlunulatus*, however, at the time of publication, the classification scheme of Bronnimann (1955 and 1960) was still being widely debated.

Bronnimann (1969, 1976, 1977) discusses and classifies numerous other fossil fecal pellets. These along with more recent works such as Blau and Grun (1989), Kuss and Senobari-Daryan (1992), Senobari-Daryan and Grotsch (1992) and Blau et al. (1995) have led to the identification of at least 9 ichnogenera and at least 50 ichnospecies of fecal pellets. Fossilized fecal pellets such as these are identified as early as the Devonian (Herbig, 1993), and are abundant throughout the Mesozoic.

**Study Area**

The study area is located along the Red Deer River between the townsites of East Coulee and Dorothy, Alberta, Canada (Fig. 4). Excellent outcrop exposures that are approximately 60 meters thick exist on both sides of the river. These outcrops are composed primarily of siliciclastic sediments belonging to the Bearpaw Formation and the Horseshoe Canyon Formation. Deposits visible along the river represent a suite of marine, marginal marine, and continental facies. These facies commonly contain an abundant, diverse trace fossil assemblage.

The trace fossil samples discussed in this paper were collected from an outcrop referred to as *Ophiomorpha* Heaven by Saunders (1989) (Fig. 4). As can

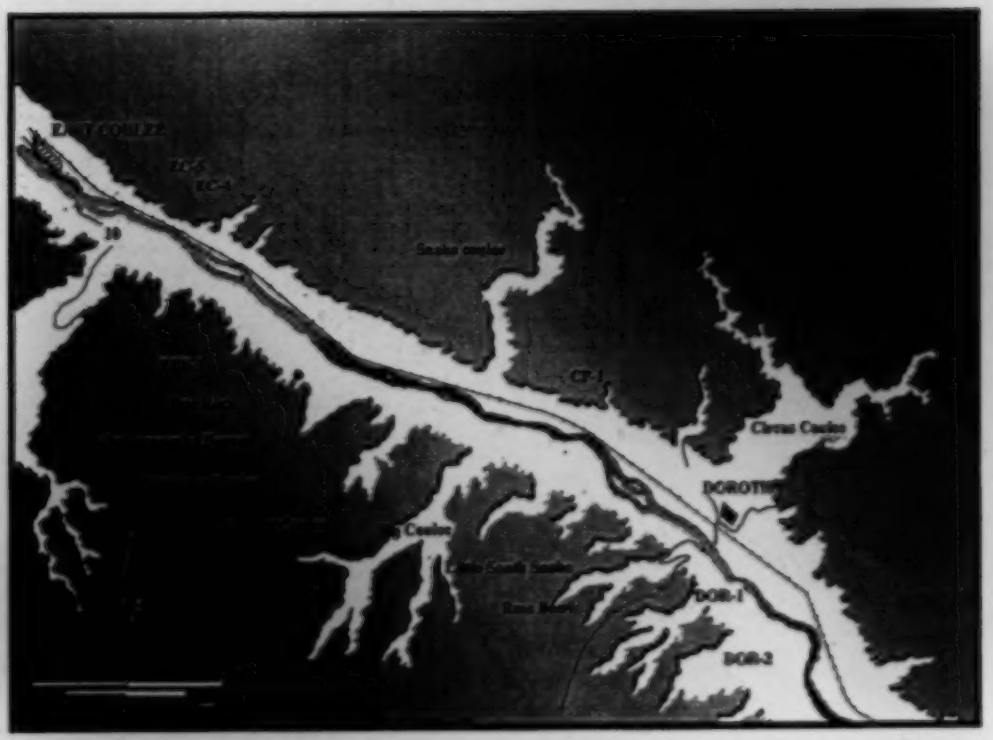



Figure 4: Location of the *Ophiomorpha* Heaven outcrop relative to East Coulee, Alberta. The location of East Coulee can be found on figure 1.1B in Chapter I.

be deduced from the name, *Ophiomorpha* Heaven houses an extensive burrow trace system that consists almost entirely of *Ophiomorpha borneensis* (fig. 1B, C and D). Thin sections of the burrow traces reveal numerous fecal pellets preserved within the fills (Fig. 5).

The facies containing the *Ophiomorpha borneensis* consists of coarsening upward very fine to fine grained, hummocky to swaley cross-stratified sandstone. This facies is interpreted by Saunders (1989) to represent storm dominated lower shoreface deposits. This facies correlates to F8 in the P3 depositional cycle in this thesis, which is also interpreted to represent storm-influenced lower to middle shoreface deposits. Further discussion of the burrow traces and the *Ophiomorpha* Heaven outcrop can be found in Saunders (1989).

**Observations**

*The burrow trace*

The walls of most of the *Ophiomorpha borneensis* collected at *Ophiomorpha* Heaven are composed of the regularly distributed, densely packed bilobate spheroids that characterize the ichnospecies (Fig. 1). Individual spheroids range between 1.5-6.0 mm in height, 2.0-5.0 mm in width, and 3.0-13.0 mm in length. Burrow walls are one spheroid thick.

Thin sections indicate that both the burrow trace fills and walls consist of individual sand sized grains of quartz, feldspar and some clays. Sideritization and calcification are common. The mammalated walls and outer portions of the burrow traces may be more sideritized than the inner portions of the trace fossil. The ichnofossil fills are typically structureless, but some burrow traces have irregular linings that range between 0.5-6.0 mm and consist of sideritized mud and sand. Individual burrow traces are circular to elliptical in cross-section. Most of the

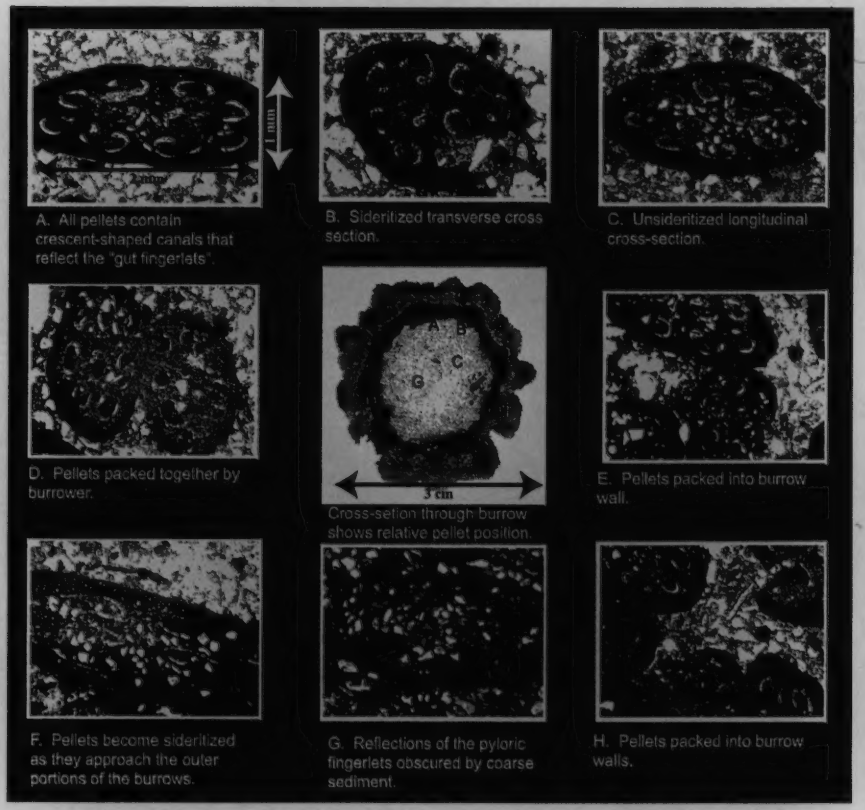

1 mm
A. All pellets contain crescent-shaped canals that reflect the "gut fingerlets".
B. Sideritized transverse cross section.
C. Unsideritized longitudinal cross-section.
A
B
C
G
3 cm
Cross-section through burrow shows relative pellet position.
D. Pellets packed together by burrower.
E. Pellets packed into burrow wall.
F. Pellets become sideritized as they approach the outer portions of the burrows.
G. Reflections of the pyloric fingerlets obscured by coarse sediment.
H. Pellets packed into burrow walls.

**Figure 5: Thin section photos of the fecal pellets. All samples were collected from *Ophiomorpha* Heaven (Fig. 4).**

*Ophiomorpha borneensis* range between 0.4-4.0 cm in diameter.

*The fecal pellets*

Thin sections of the *Ophiomorpha borneensis* contain abundant fecal pellets that are randomly distributed throughout both the burrow trace walls and fills (fig. 5). Only one type of fecal pellet is present in the thin sections.

The fecal pellets are circular to elliptical in shape, and may possess slightly wavy profiles. The pellets are typically between 1.5-2.3 mm in the longitudinal direction, with an average of approximately 1.8 mm. In the shorter direction, pellets normally range between 0.8-1.4 mm in diameter, with an average of approximately 1 mm.

Transverse sections through the fecal pellets show crescent shaped canals organized in two bilaterally symmetrical groups of five canals each. These fecal pellets are identified to be *Palaxius decemlunulatus* based on their 10 crescent-shaped internal canals. Individual crescents tend to be thin and strongly arched with dilated tips. The concave sides of the crescents are typically oriented towards the centers of the individual symmetrical groups of five canals.

The fecal pellets consist primarily of sideritized to calcified clay. Some of the pellets contain individual sand sized grains of quartz and feldspar, although these are not abundant. It appears that the individual canals are composed predominantly of calcified material, whereas the remainder of the fecal pellets are more typically characterized by siderite. In general, a greater degree of sideritization is seen within the concavity of individual canals, and around the outside edges of the fecal pellets.

**Discussion**

Burrows may house multiple species (MacGinitie, 1934), and as such, it is possible that the fecal pellets described here were not deposited by the *Ophiomorpha*

tracemaker. However, the *Palaxius decemlunulatus* are believed to have been deposited by the *Ophiomorpha* tracemaker because it is the only type of fecal pellet present, and the pellets are abundant, and randomly distributed throughout both the burrow trace walls and fills. In modern sediments, fecal pellets similar to those described here are commonly found associated with the burrow system of the tracemaker that deposited them (Pryor, 1975).

The significance of the *Palaxius decemlunulatus* is debatable, however. Moore (1939) indicated that the particular number, shape, and organization of the internal canals in the coprolites is species specific in the modern record. Bronnimann (1955) based his classification of fossil fecal pellets on this statement. Fossil workers then took the classification one step further, and began assigning fossilized fecal pellets to tribes/families etc. of modern organisms. For example, Bronnimann *et al.* (1972) indicated that *Thoronetia* isp. (which possess ventral caps) were deposited by ancestors of the modern tribe Galatheidea, because Moore (1932) showed that the pellets of the Galatheidea possess a ventral cap. Senowbari-Daryan (1979) indicated that *Palaxius* isp. belong to the modern Axiidae family, as Moore (1932) showed that the feces produced by *Axius stirhynchus* contained crescent-shaped canals.

These conclusions are premature and cannot be substantiated. Pryor (1975) showed that the fecal pellets of *Callichirus* (as *Callianassa*) *major* contain crescent shaped internal canals, although these organisms are not members of the Axiidae. Powell (1974) shows that the fecal pellets of *Neotrypaea* (as *Callianassa*) *californiensis* also produce fecal pellets containing crescent-shaped internal canals which are very similar to those described in the Horseshoe Canyon Formation in this study (Fig. 2C). *Neotrypaea californiensis* is not a member of the Axiidae either. In addition, Powell (1974) indicates that the fecal pellets of *Neotrypaea californiensis* possess a ventral cap, although the organism is a Thalassinid shrimp (Fig. 2C). Furthermore,

as in the case of *Callichirus major* and *Neotrypaea californiensis*, the classification of shrimp species is changing continually as new data becomes available. Assigning fossil fecal pellets directly to modern groups of organisms is not good scientific practice. There is insufficient data at present to support claims that link ancient fecal pellet deposition to modern organisms.

A second problem with the classification of ancient fecal pellets is with regards to the identification of the "ventral" side of the pellet. As in Bronnimann and Zaninetti (1972), fossil fecal pellets are commonly described with regards to their ventral and dorsal sides. Unless a ventral cap is present on the coprolites, the ventral and dorsal side of the pellet is still unknown. Hence, describing fossil fecal pellets in this manner can be misleading and confusing.

A third problem is that it is easy to incorrectly identify an ancient or modern fecal pellet if due care is not taken with the specimens. Both modern and ancient fecal pellets can be subject to high amounts of erosion and deformation. The ventral cap is commonly missing or overlooked (Powell, 1974), and the internal canal shape can easily be mis-identified. For example, Moore (1932) indicated that the fecal pellets of *Callianassa subterranea* contain 20 circular internal canals. Powell (1974) suggested that imperfect specimens may have led to this conclusion and that the 20 circular holes may represent the ends of 10 crescent-shaped internal canals similar to those of *Neotrypaea californiensis*. Thus, only the best quality specimens should be used for identification purposes to prevent incorrect descriptions from entering published literature.

**Conclusions**

Concrete evidence linking trace fossils to their tracemakers is relatively rare. Discovering identifiable fecal pellets in extensive burrow systems in the Western

Canadian Sedimentary Basin provides insight into the nature and origin of both *Ophiomorpha borneensis* and *Palaxius decemlunulatus*.

At present, there are more questions than answers with regards to the relationships between ancient and modern fecal pellets and their respective tracemakers. How can fossil fecal pellets be related to modern organisms? Does the number and organization of the internal canals change throughout time, as suggested by Bronnimann *et al.* (1972)? Does the shape of the internal canals change throughout time? Does convergent evolution play a role in this? Can the study of fossil fecal pellets help to unravel the evolutionary complexities of shrimp and other marine organisms? Further research is required to obtain an understanding of the relationships between ancient and modern fecal pellets and ancient and modern burrowers. It is hoped that studies such as this one will inspire other workers to continue to search for the answers to these questions as their results may be beneficial to paleontologists, geologists and biologists alike.

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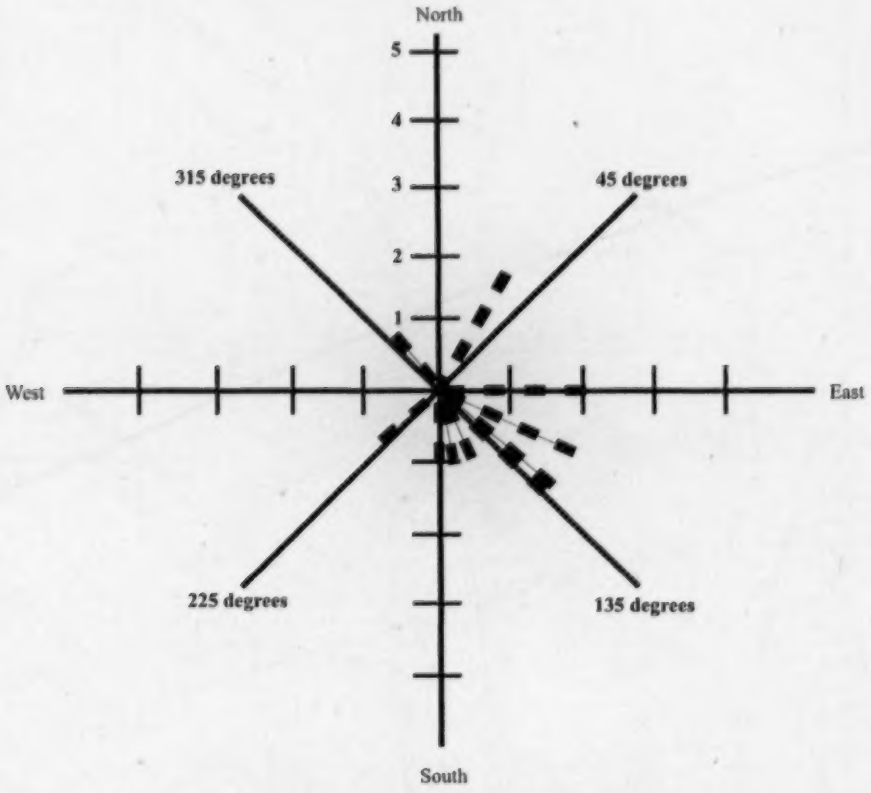
**Appendix II**

**Rose Diagram of Paleocurrent Measurements from Facies 5 in Facies Association 1**

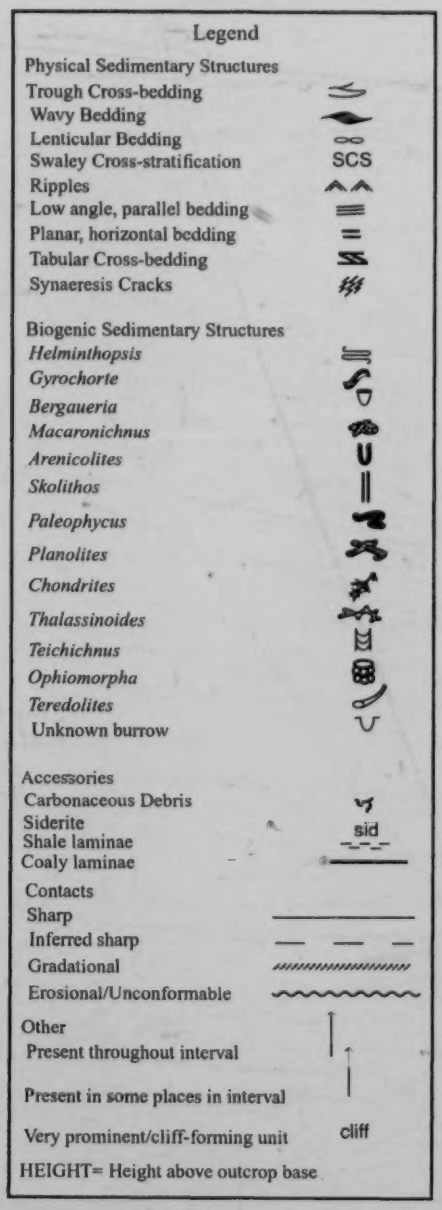


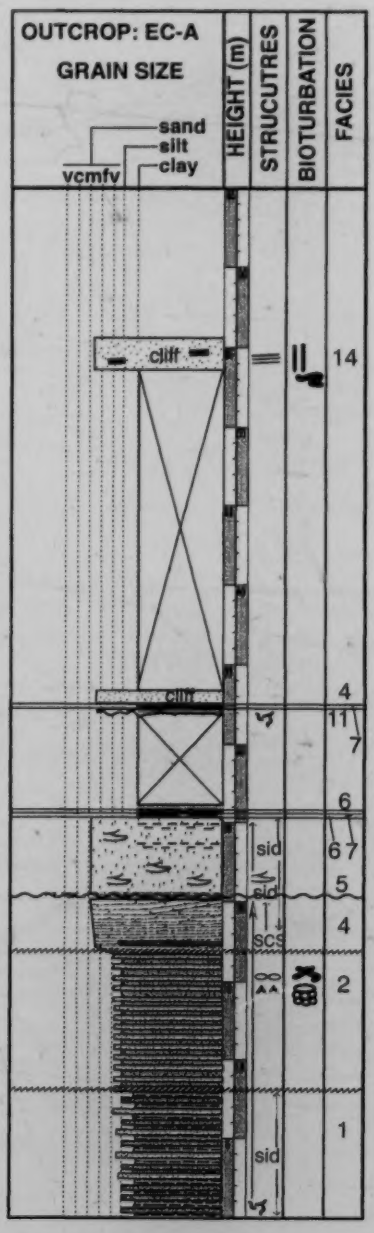

Note: The numbers 1-5 indicate the number of measurements taken.
Dotted lines indicate paleo-current direction measurements in degrees.
Note that the dominant flow direction is towards the southeast.

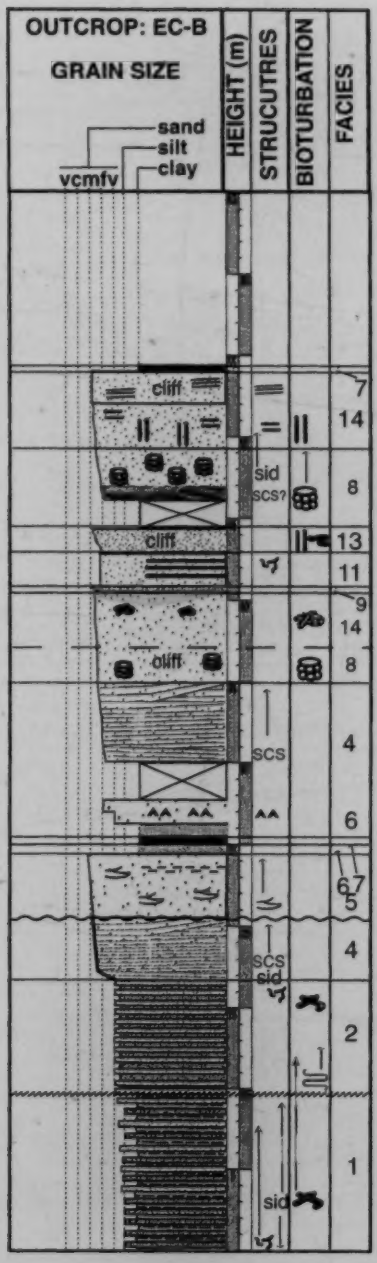
# APPENDIX III
# OUTCROP LITHOLOGS



Appendix III contains lithologs for most of the measured sections discussed in this thesis. Outcrop locations are shown on Fig. 1.1D in Chapter I. The legend applies to all lithologs in Appendix III.




OUTCROP: EC-B
GRAIN SIZE
sand
silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
cliff
cliff
cliff
sid
scs?
scs
scs
sid
sid
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14
8
13
11
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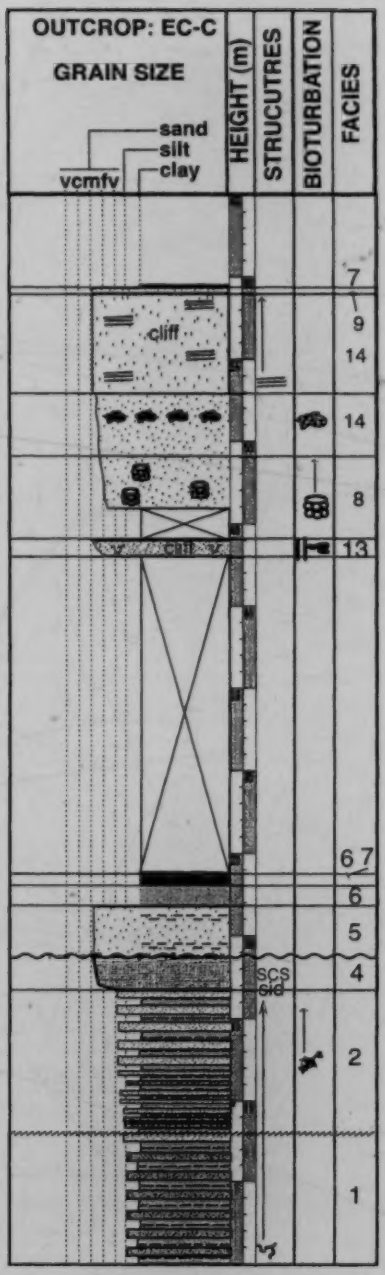
4
2
1


OUTCROP: EC-C
GRAIN SIZE
sand
silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
cliff
cliff
scs
sid
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2
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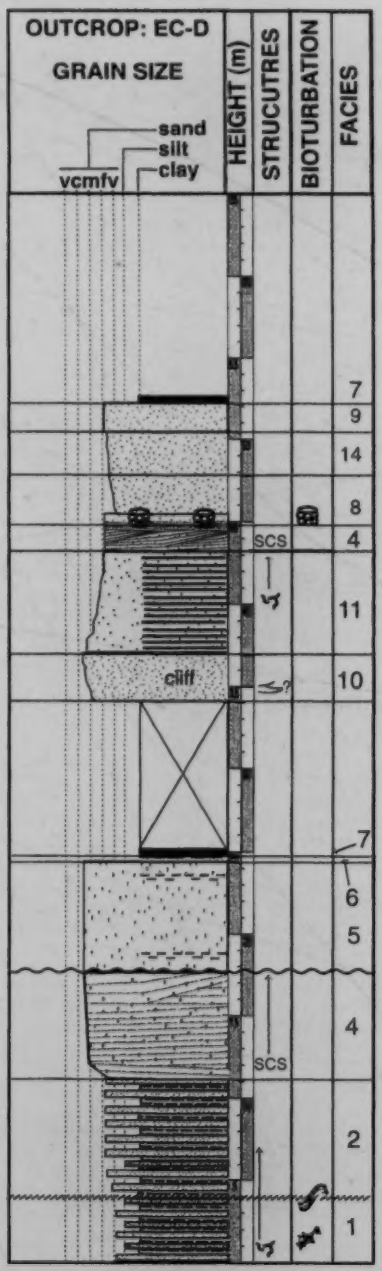
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silt
clay
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HEIGHT (m)
STRUCUTRES
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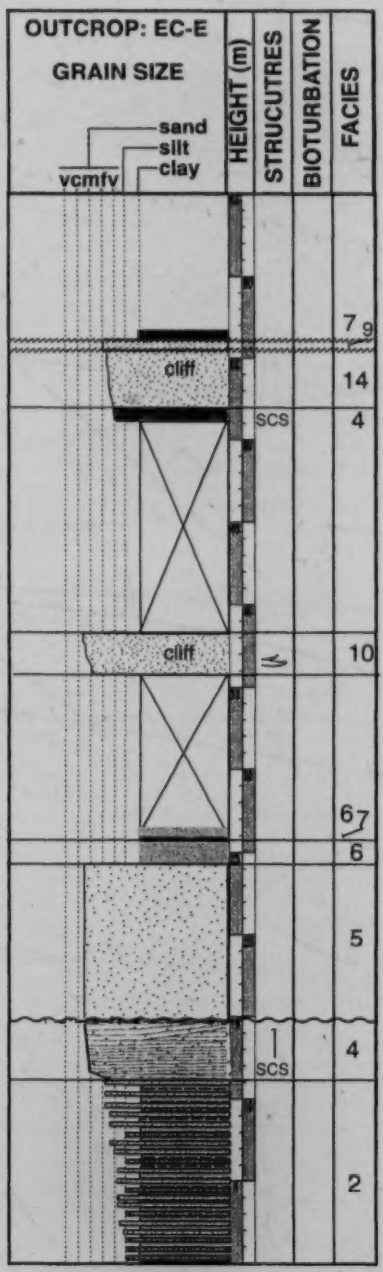
1
SCS
cliff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silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
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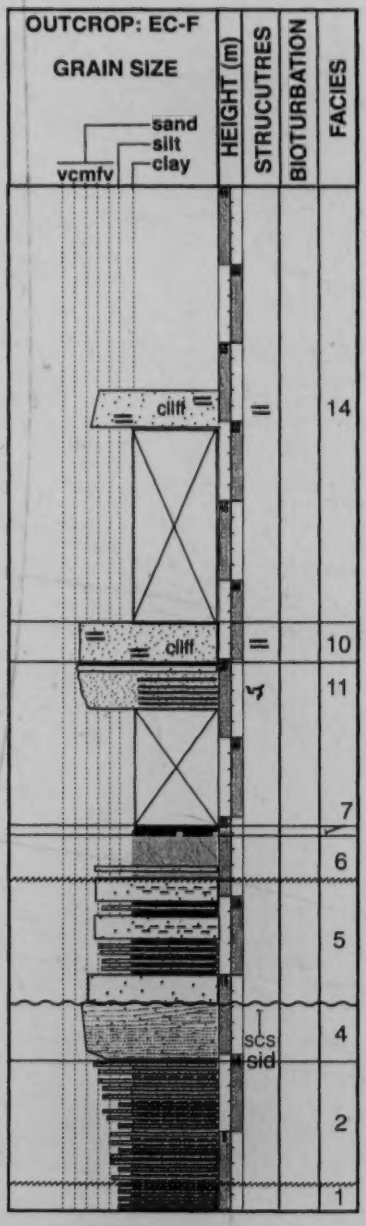
2
SCS
cliff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silt
clay
vcmfv
HEIGHT (m)
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BIOTURBATION
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cliff
scs
sid
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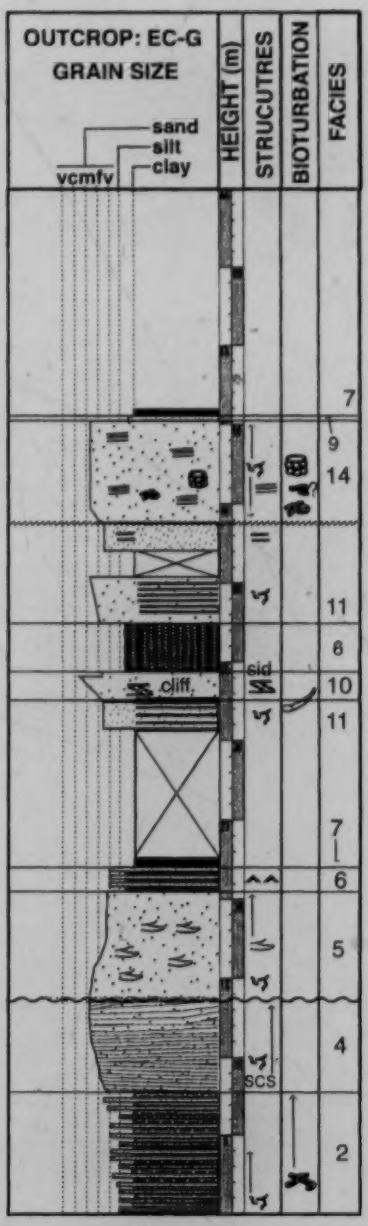
OUTCROP: EC-G
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silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
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sid
cliff
SCS
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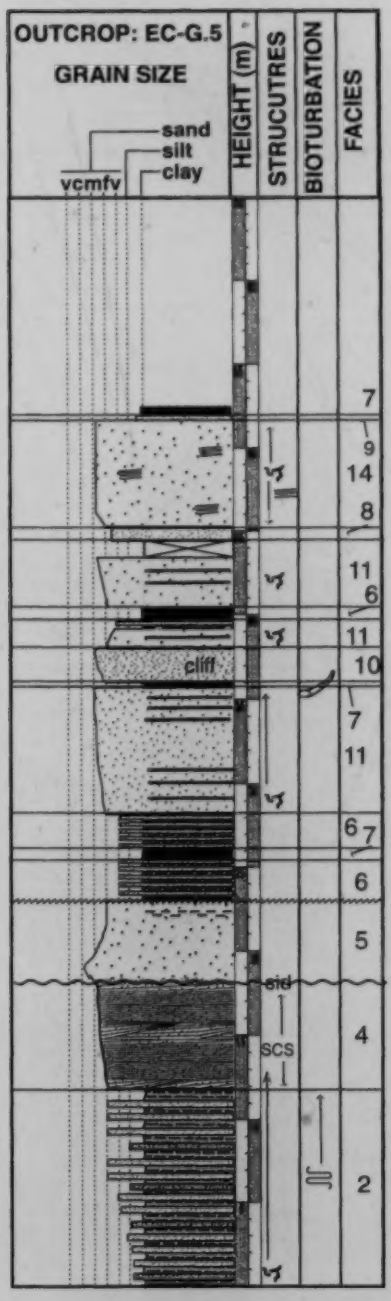
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GRAIN SIZE
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silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
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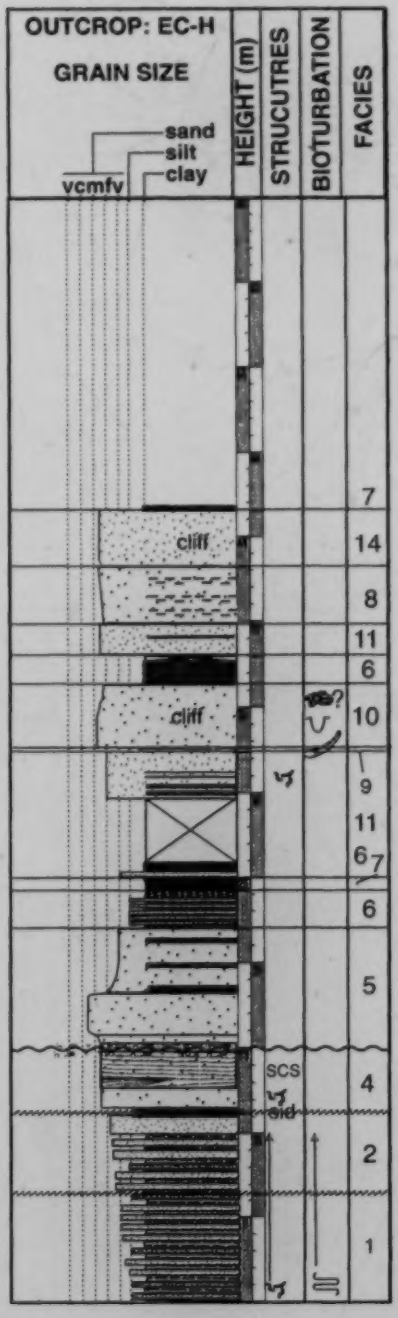
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sand
silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
cliff
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sid
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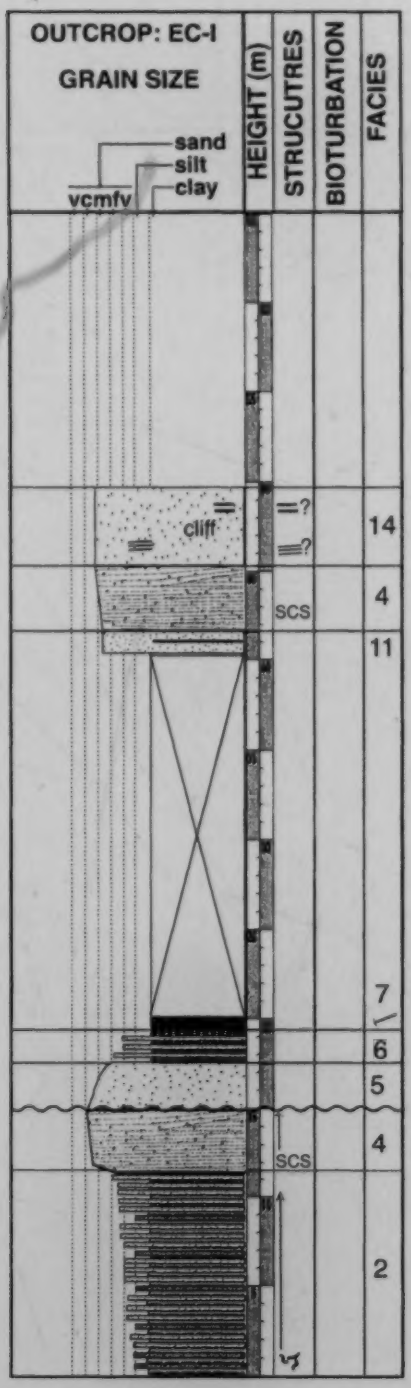
OUTCROP: EC-I
GRAIN SIZE
sand
silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
cliff
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SCS
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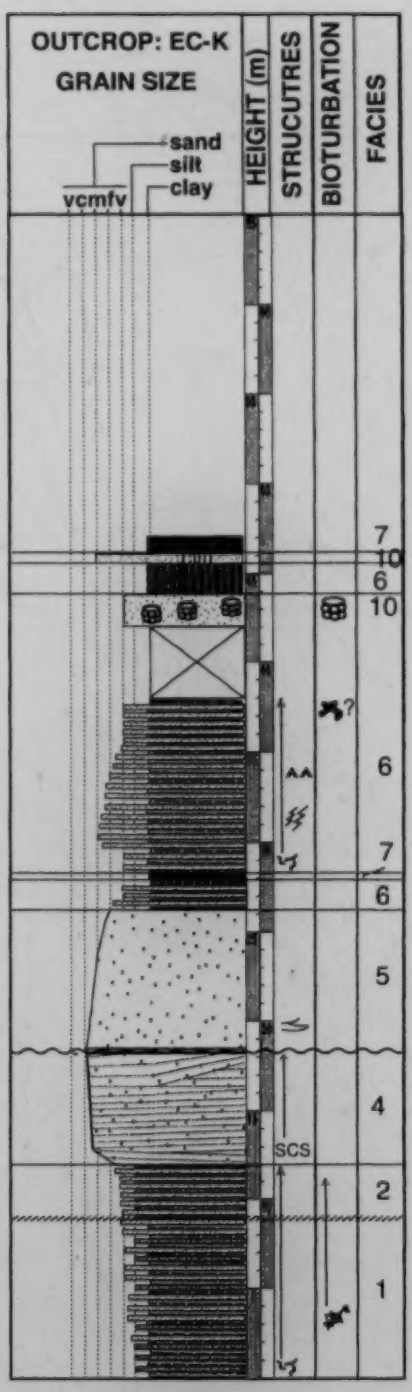
OUTCROP: EC-K
GRAIN SIZE
sand
silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
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SCS
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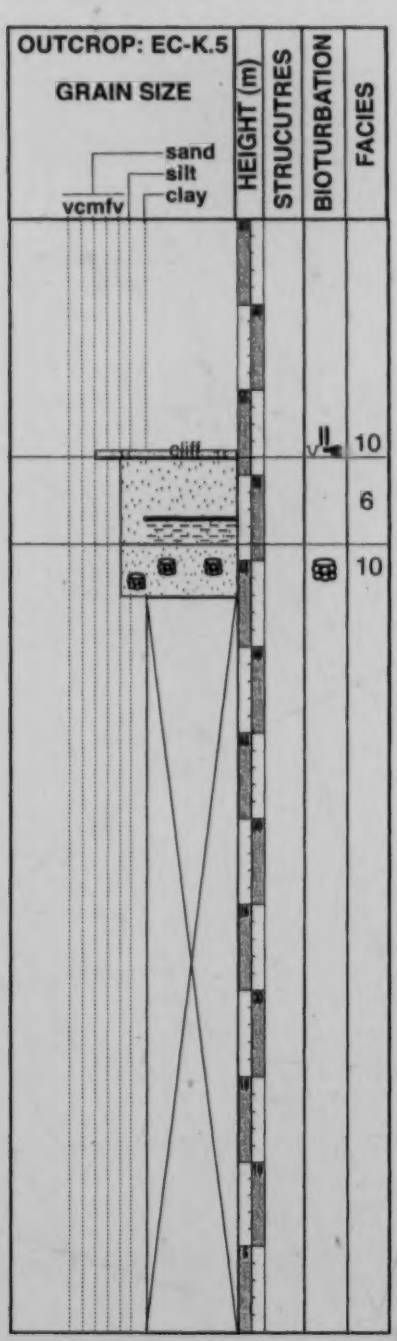
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silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
cliff
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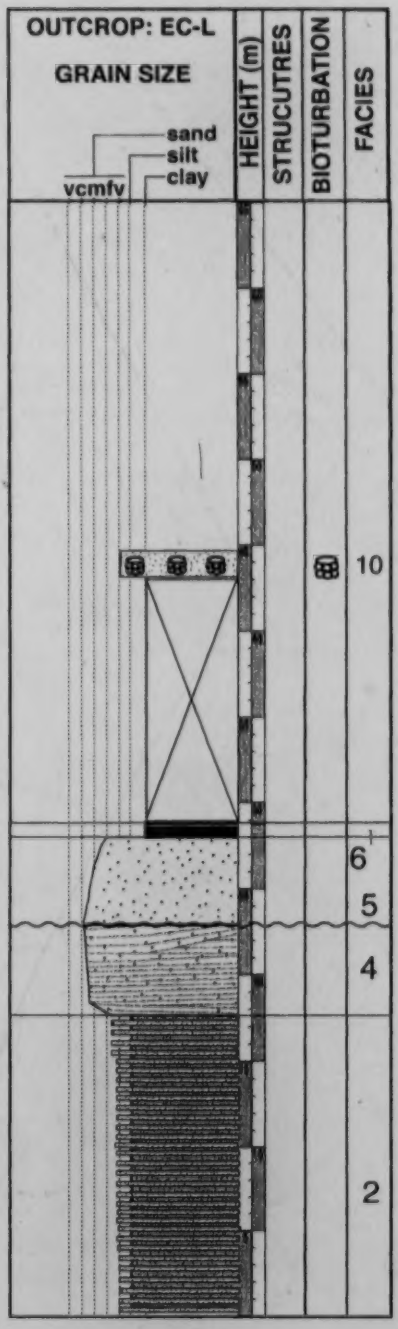
OUTCROP: EC-L
GRAIN SIZE
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silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
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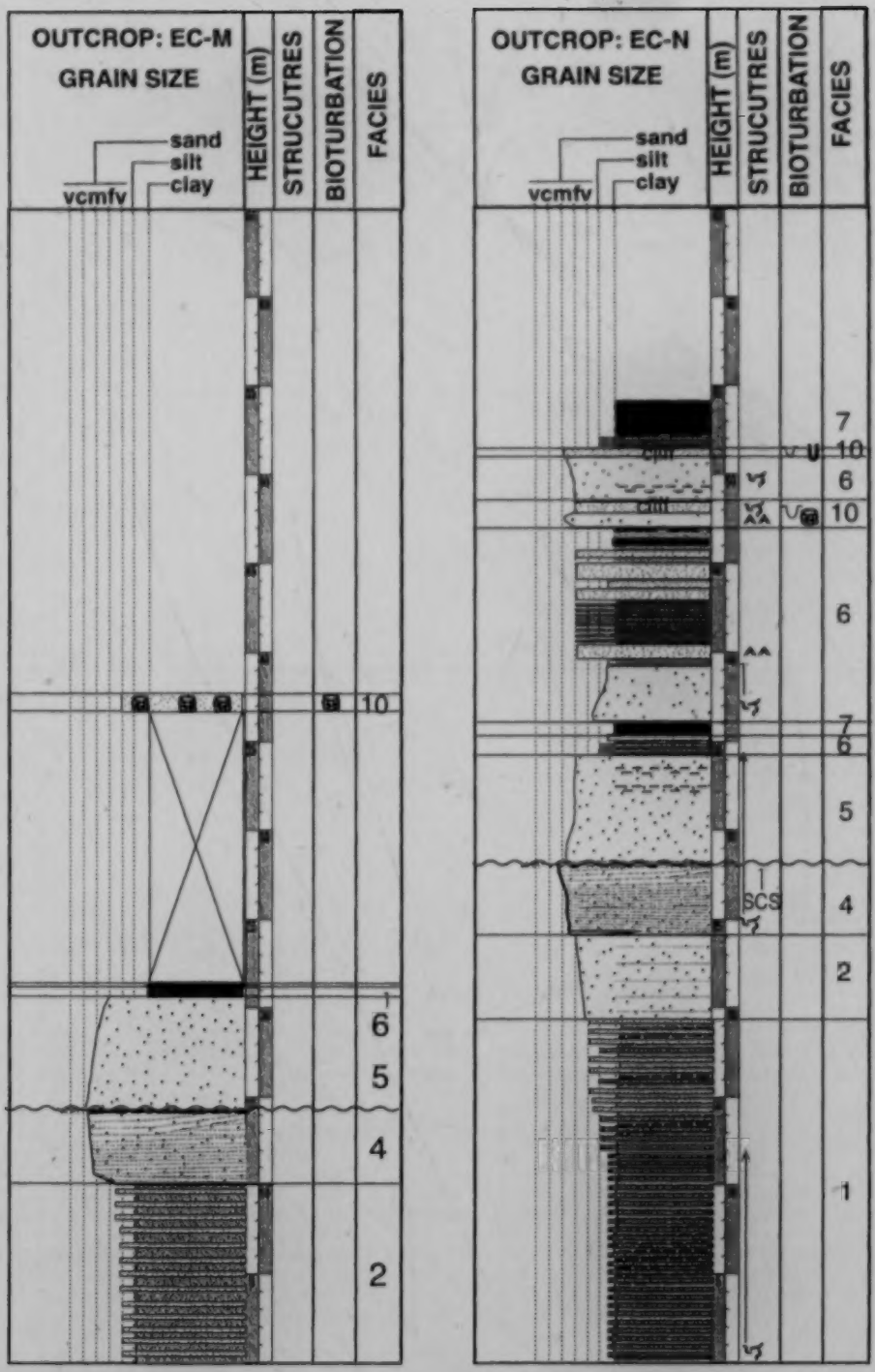
OUTCROP: EC-M
GRAIN SIZE
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silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
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OUTCROP: EC-N
GRAIN SIZE
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clay
vcmfv
HEIGHT (m)
STRUCTURES
BIOTURBATION
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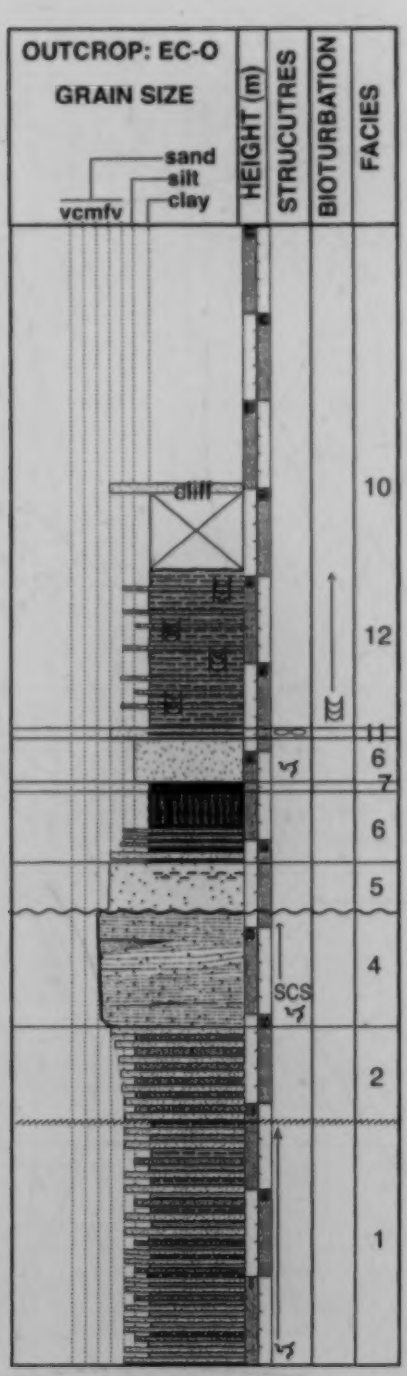
OUTCROP: EC-O
GRAIN SIZE
sand
silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
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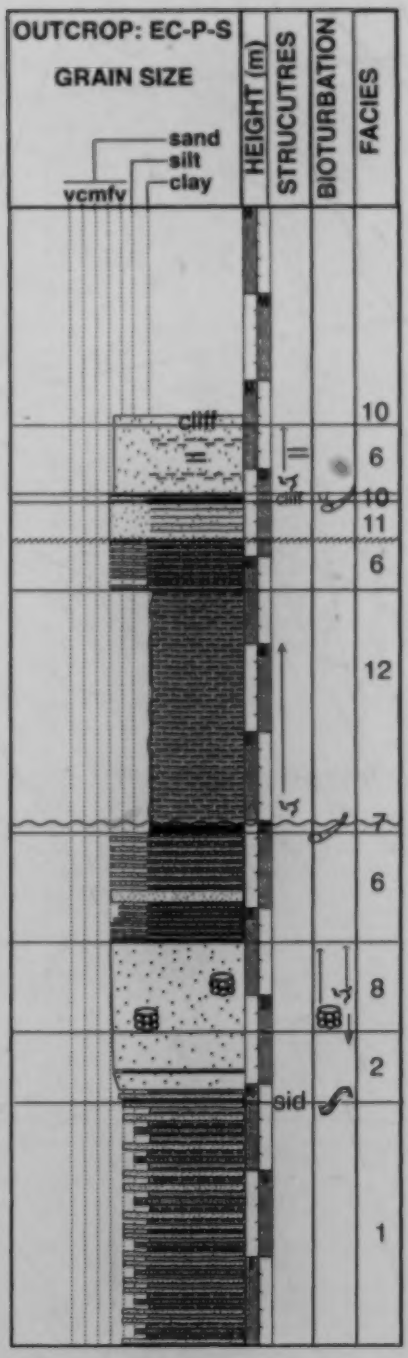
OUTCROP: EC-P-S
GRAIN SIZE
sand
silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
cliff
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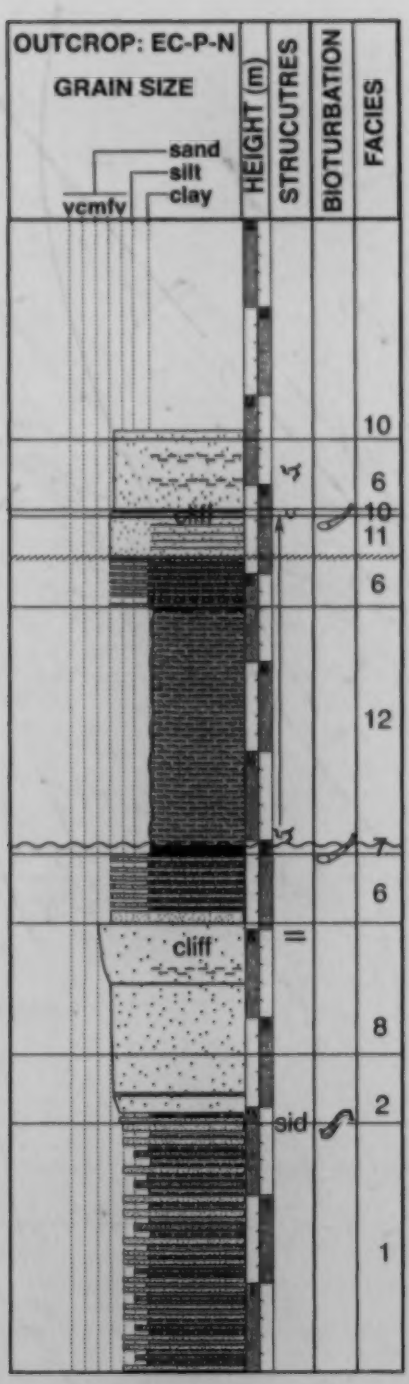
OUTCROP: EC-P-N
GRAIN SIZE
sand
silt
clay
vcmfv
HEIGHT (m)
STRUCUTRES
BIOTURBATION
FACIES
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cliff
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cliff
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